Cart3D Simulations for the 2nd AIAA Sonic Boom Prediction Workshop

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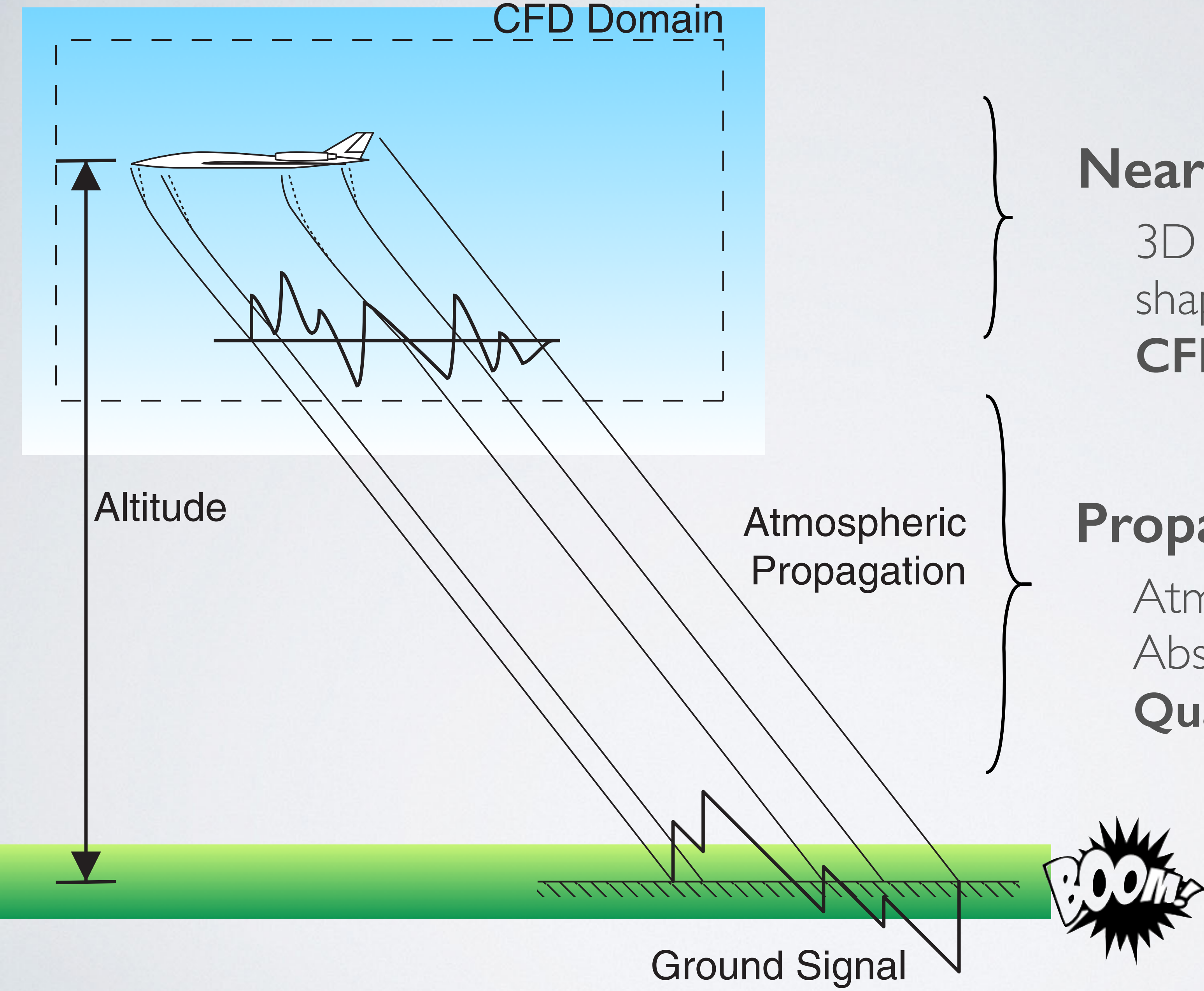
MOTIVATION

- **Commercial supersonic flight** banned over the US because of objectionable sonic boom
- Hope to overturn this with demonstrably quiet aircraft (e.g. QueSST)
- **CFD tools are a major contributor to design efforts**
- Sonic Boom Prediction Workshops
    - (2008) NASA FAP SBPW
    - (2014) AIAA SBPW1
    - ➡ **(2017) AIAA SBPW2**

Sonic Boom Physics



Nearfield

3D effects (aircraft shape and plume)

CFD

Propagation

Atmospheric variability

Absorption

Quasi-1D PDE

OUTLINE

- Nearfield Workshop
- Propagation Workshop
- Conclusions

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Cart3D Simulations for the Second AIAA Sonic Boom Prediction Workshop

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Simulation results are presented for all test cases prescribed in the Second AIAA Sonic Boom Prediction Workshop. For each of the four nearfield test cases, we compute pressure signatures at specified distances and off-track angles, using an inviscid, embedded-boundary Cartesian-mesh flow solver with output-based mesh adaptation. The cases range in complexity from an axisymmetric body to a full low-boom aircraft configuration with a powered nacelle. For efficiency, boom carpets are decomposed into sets of independent meshes and computed in parallel. This also facilitates the use of more effective meshing strategies — each off-track angle is computed on a mesh with good azimuthal alignment, higher aspect ratio cells, and more tailored adaptation. The nearfield signatures generally exhibit good convergence with mesh refinement. We introduce a local error estimation procedure to highlight regions of the signatures most sensitive to mesh refinement. Results are also presented for the two propagation test cases, which investigate the effects of atmospheric profiles on ground noise. Propagation is handled with an augmented Burgers' equation method (NASA's sBOOM), and ground noise metrics are computed with LCASB.

Nomenclature

A_{ref}	Reference area
$C_{D/L/M}$	Drag/lift/pitching moment coefficients
C_p	Local pressure coefficient
ϵ	Integrated signature differences
E	Local error estimate
$\mathcal{J}$	Aerodynamic output functional
ℓ	Distance along signature
L	Reference length for propagation
M	Mach number
p	Static pressure
p	Order of convergence
r	Distance from flight path
T	Temperature
w	Weight in functional
α	Angle of attack
β	$\sqrt{M_\infty^2 - 1}$
θ	Offset angle to avoid sonic glitch
μ	Mach angle $= \sin^{-1}(1/M_\infty)$
ρ	Density
τ	Normalized x-distance from nose Mach cone
Φ	Off-track/Azimuthal angle

Subscripts

$(\cdot)_\infty$	Freestream value
$(\cdot)_t$	Stagnation value
$(\cdot)_c$	Coarse
$(\cdot)_f$	Fine
$(\cdot)_m$	Medium

Abbreviations

ASEL/CSEL	A-/C-weighted sound exposure level
AXIE	Axisymmetric body (Case I)
AXIE-PROP	Axisymmetric body (Prop. Case I)
C25F	C25D with flow-through nacelle (Case III)
C25P	C25D with powered nacelle (Case IV)
JWB	JAXA wing–body (Case II)
LCASB	Loudness Code for Asymmetric Sonic Booms
LM–1021	Lockheed Martin 1021 (Prop. Case II)
PL	Perceived level of noise
SBPW	Sonic Boom Prediction Workshop

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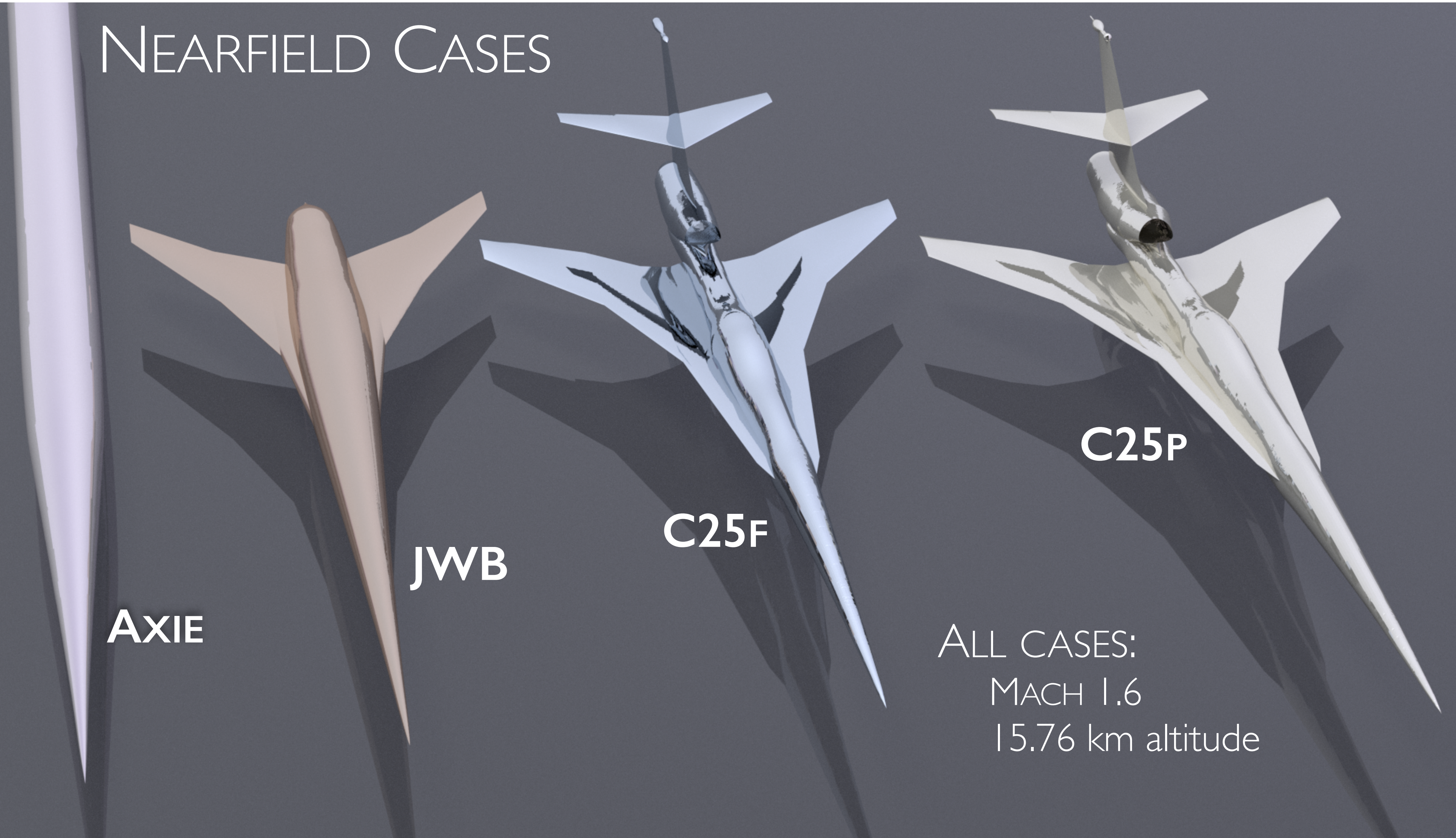
ALL REQUIRED AND OPTIONAL CASES FROM BOTH WORKSHOPS

OUTLINE

- **Nearfield Workshop — Cart3D**
  - **Meshing approach** — Alignment + Adaptation
  - **Boom Carpets** — Azimuthal Alignment
  - **Results** for Cases I, II, IV
  - **Local Error Analysis**
- **Propagation Workshop**
- **Conclusions**

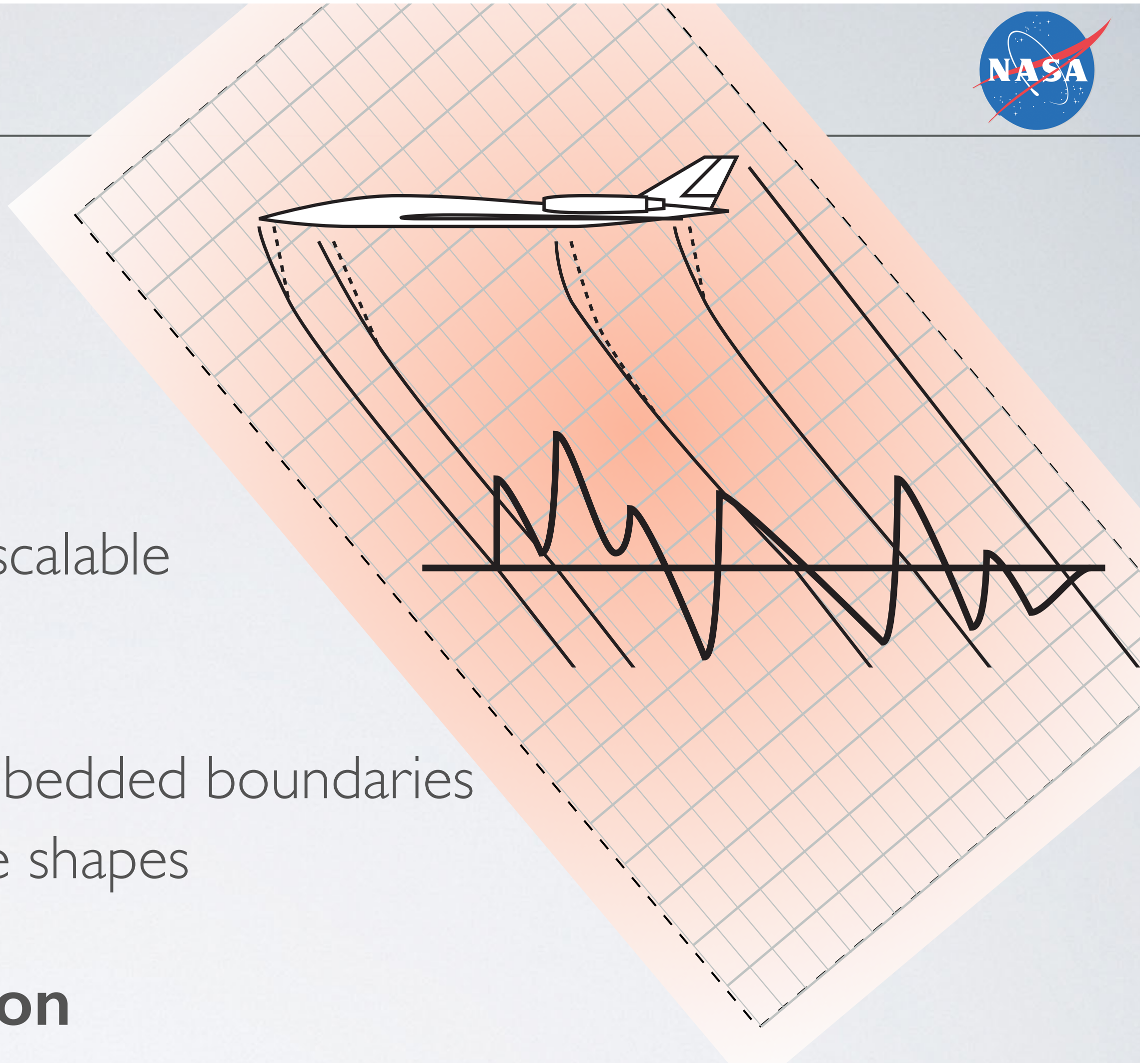
Nearfield Cases



Submitted:

- All 4 cases, all azimuths, 3 mesh refinement levels
- Propagated signals and loudness metrics

CFD and Meshing



Flow Solver — Cart3D v1.5

- Steady, inviscid flow
- 2nd-order upwind method
- Multigrid acceleration
- Domain decomposition — highly scalable

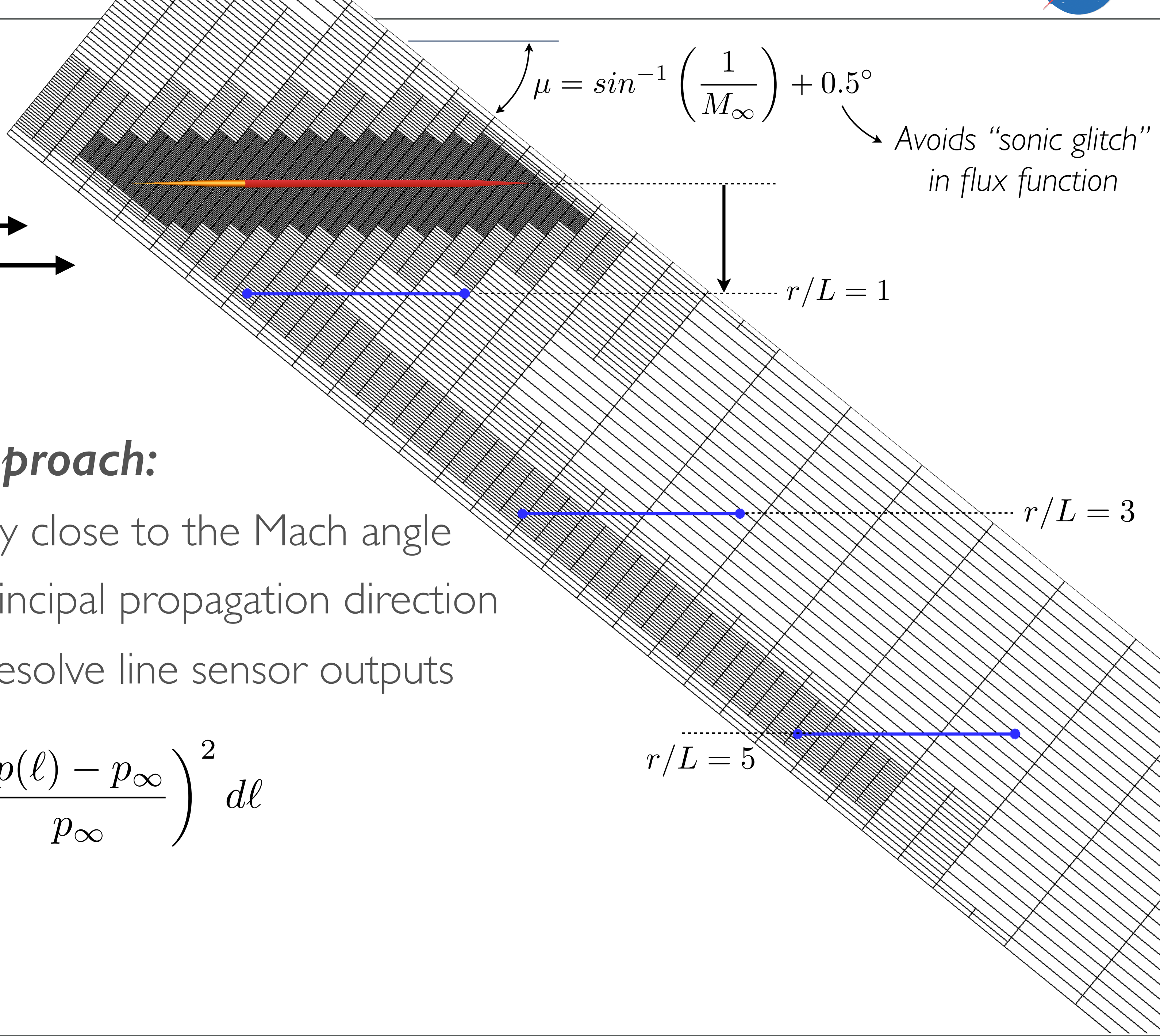
Automatic Meshing

- Multilevel Cartesian mesh with embedded boundaries
- Handles arbitrarily complex vehicle shapes

Goal-Oriented Mesh Adaptation

- Mesh automatically refined in locations with most impact on signatures
- Discretization error estimates computed via adjoint method

MESHING

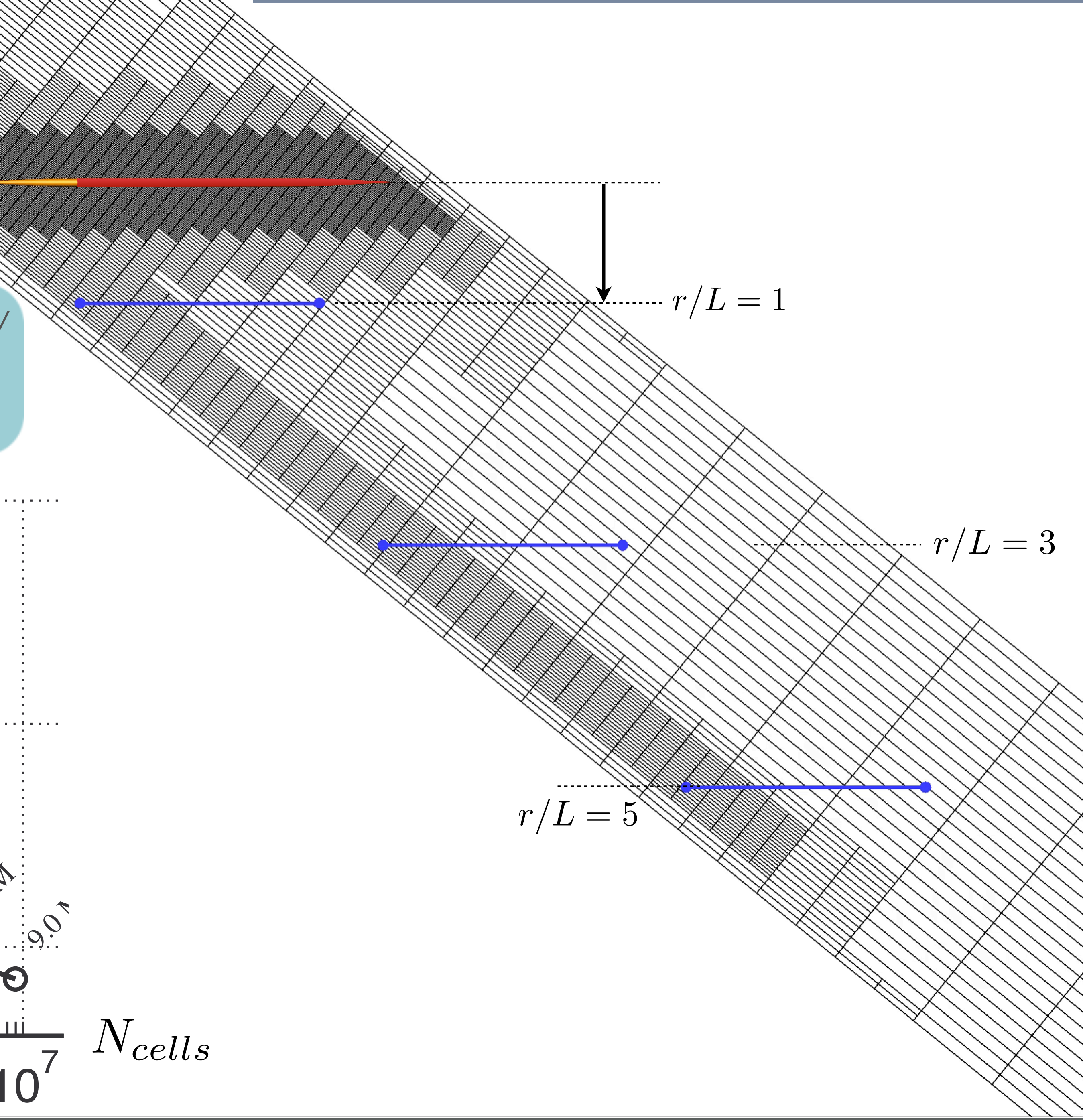


Basic Meshing Approach:

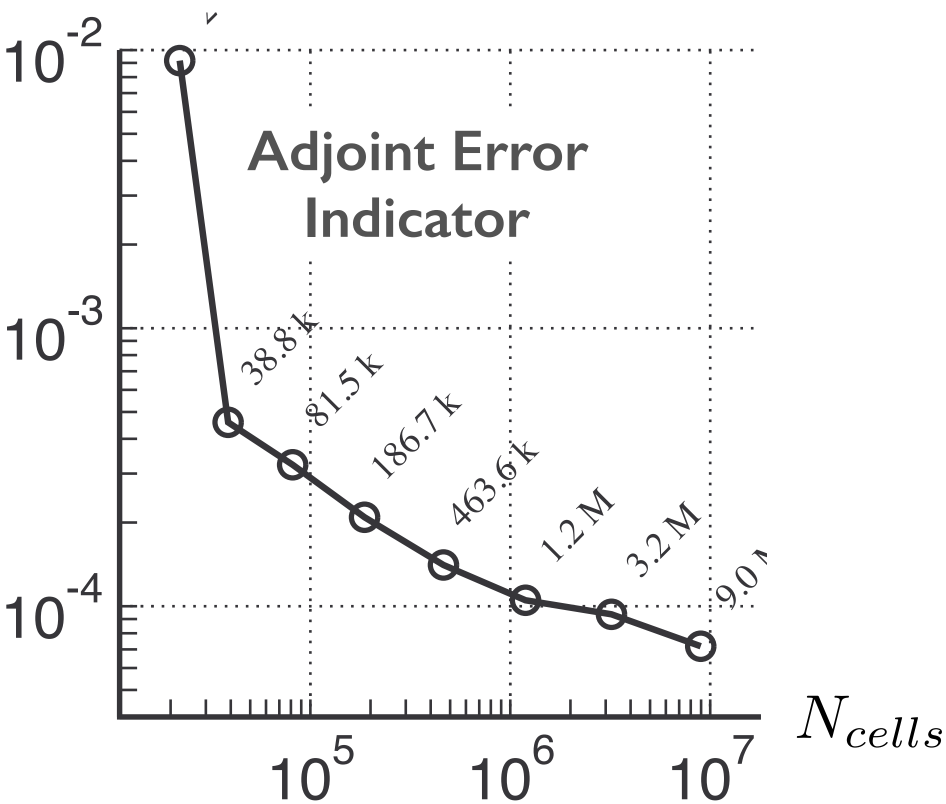
- **Rotate** mesh very close to the Mach angle
- **Stretch** in the principal propagation direction
- **Adapt** mesh to resolve line sensor outputs

$$\mathcal{J}_r = \int_0^L w(\ell)\left(\frac{p(\ell) - p_\infty}{p_\infty}\right)^2 d\ell$$

ADAPTATION



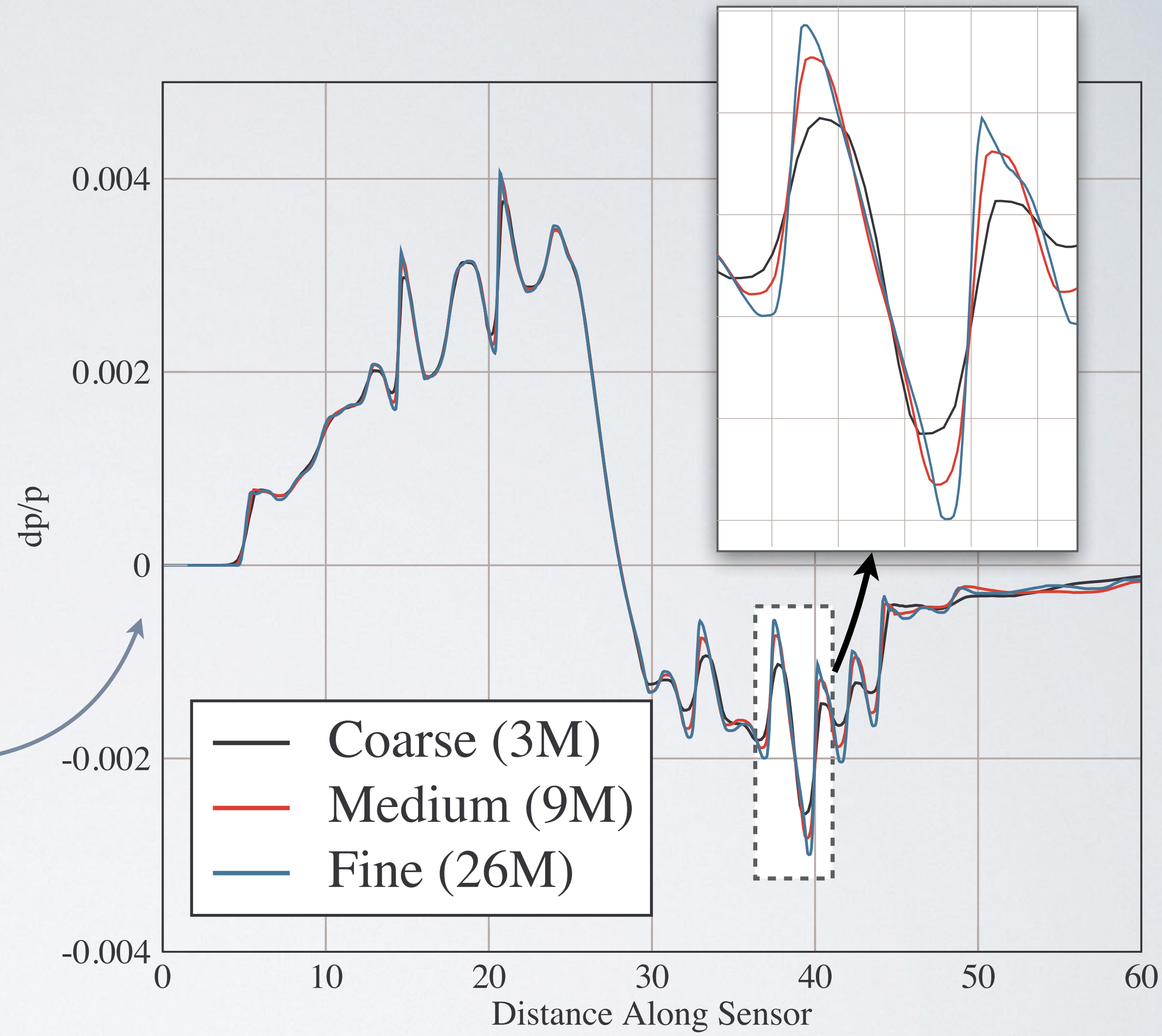
Adapt mesh locally to accurately compute off-body signatures (adjoint-weighted residuals)



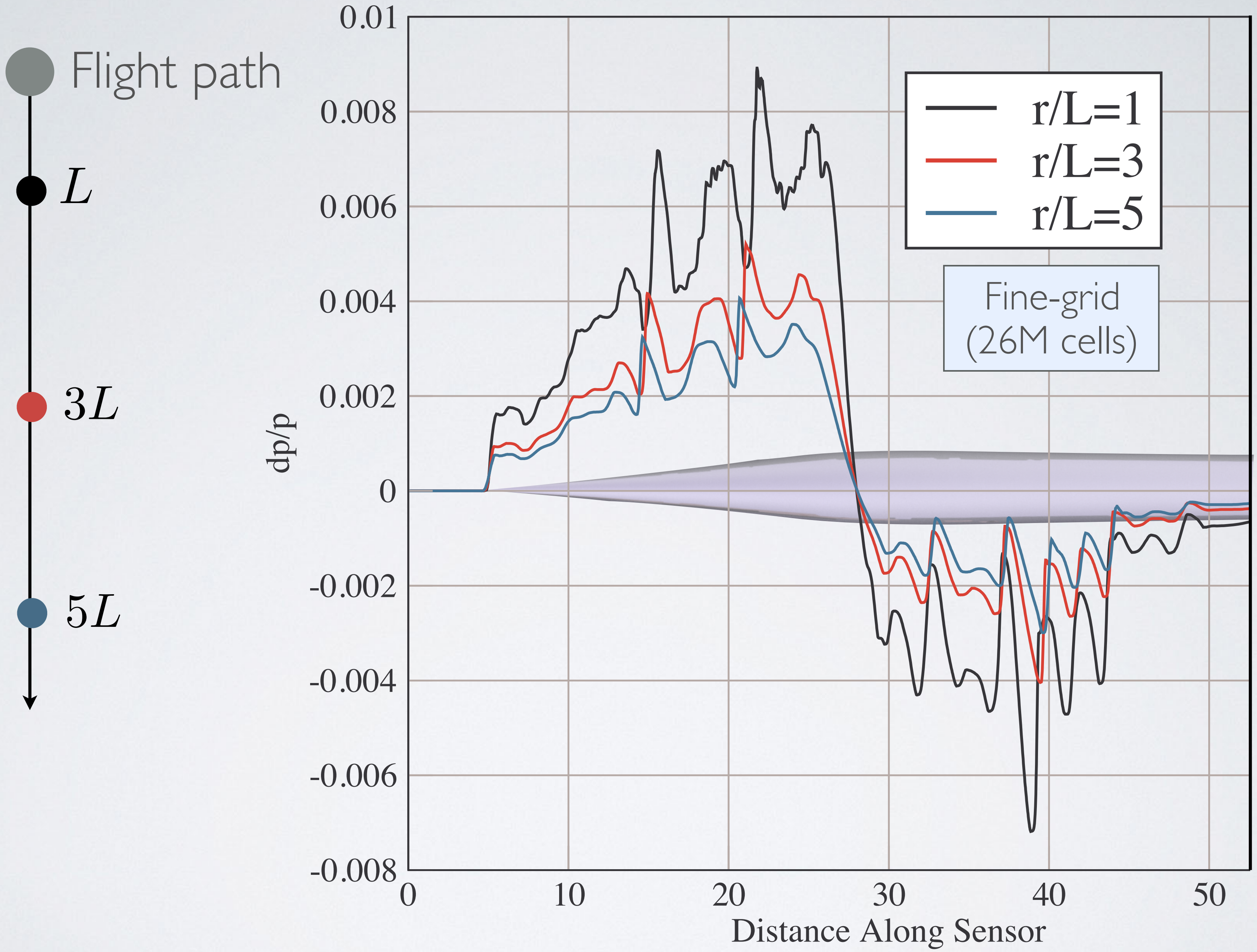
Mesh Convergence Guidelines

Submit **"coarse"**, **"medium"**, **"fine"** mesh solutions

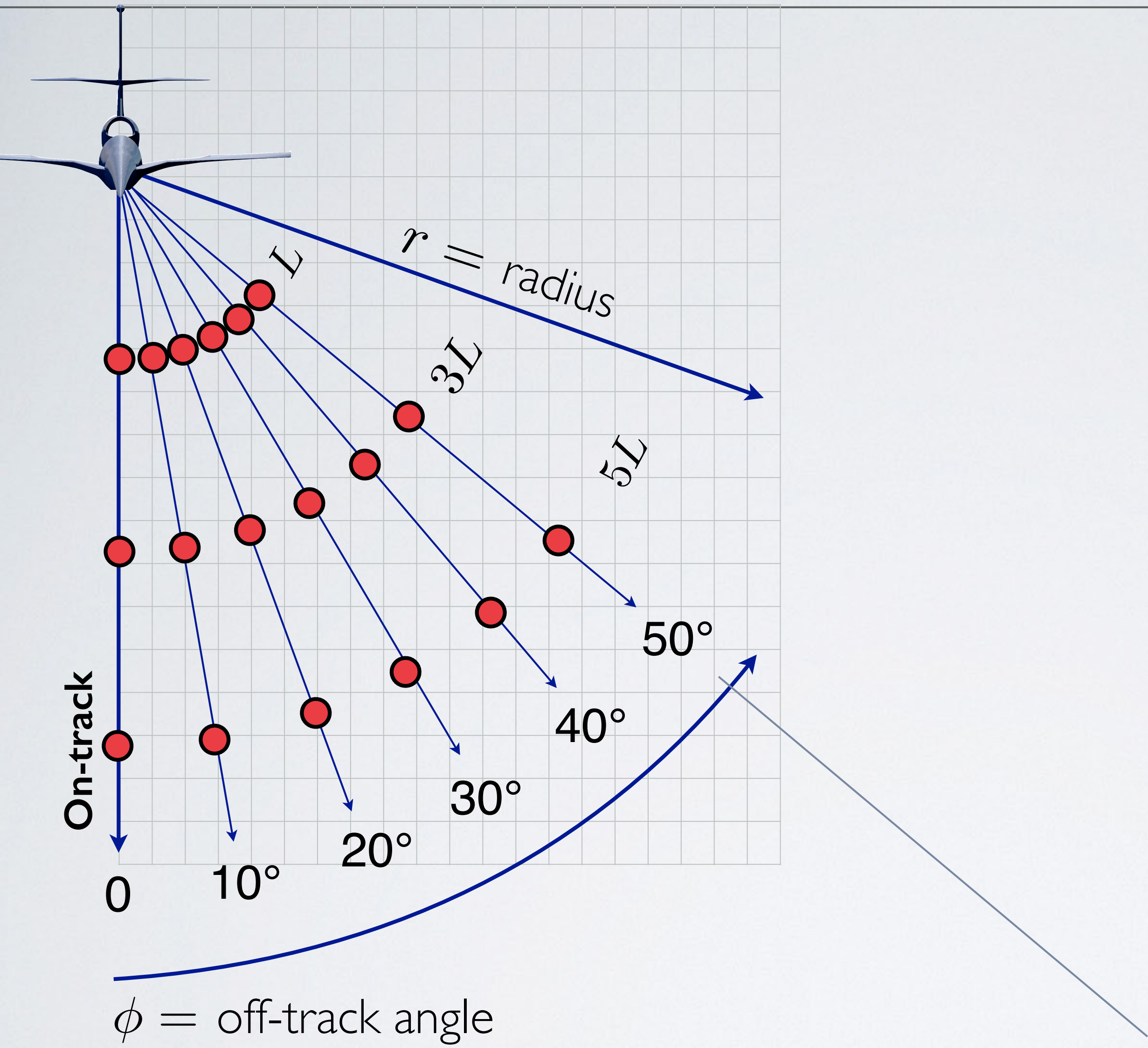
- **Quantitative guideline:** Asymptotic convergence of pressure functionals
- **Qualitative guidelines:** Consistent signal features over consecutive meshes



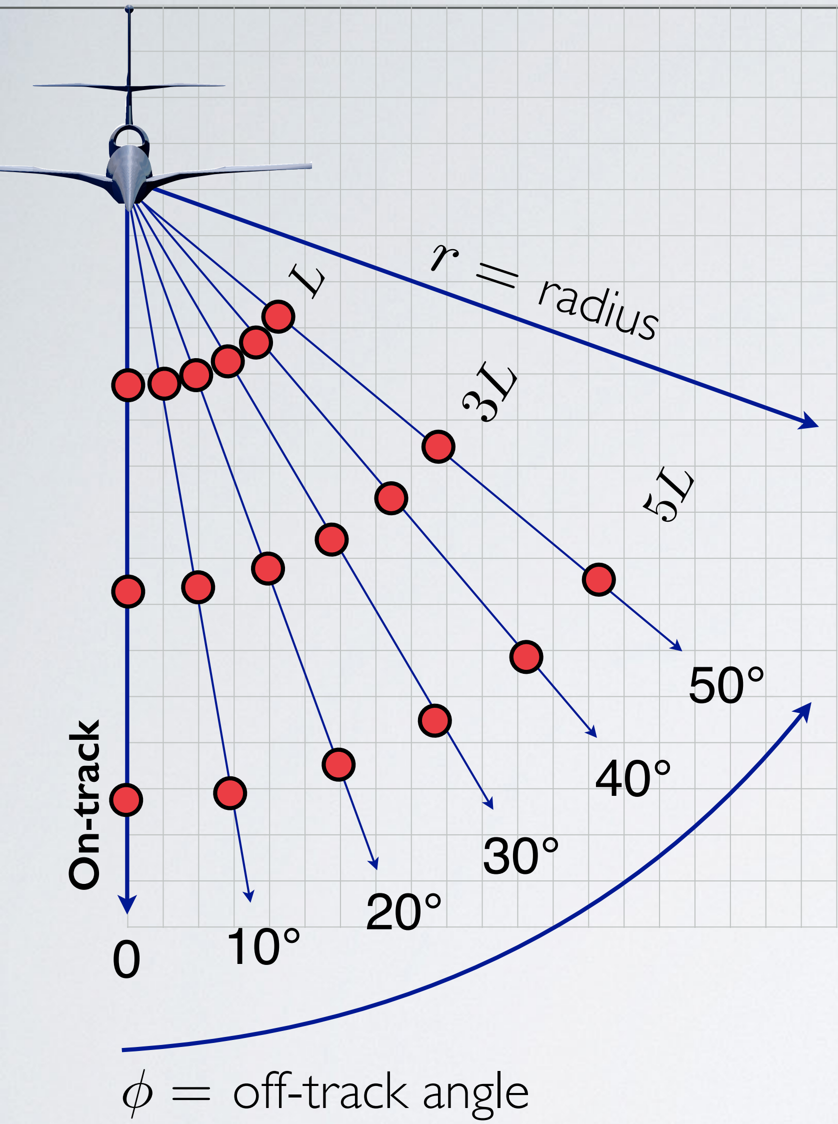
AXIE — SIGNALS



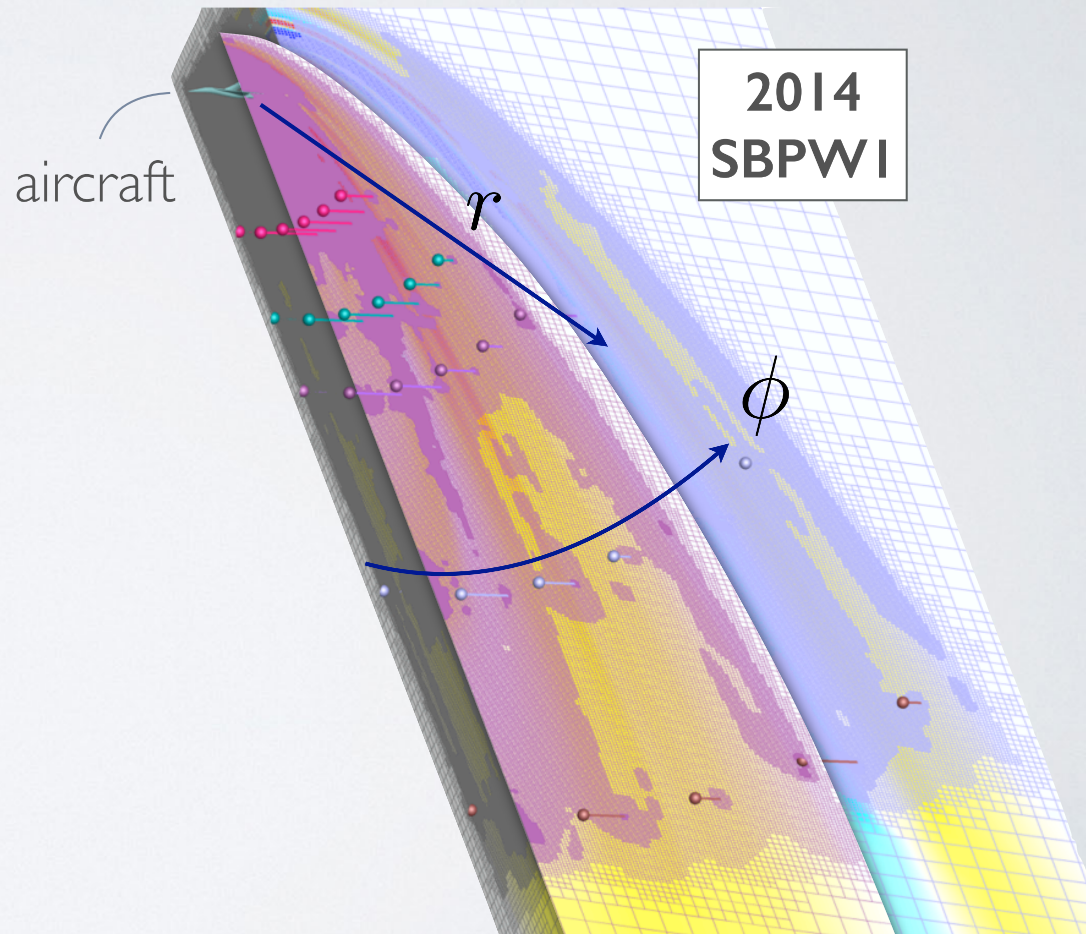
OFF-TRACK SIGNATURES



OFF-TRACK SIGNATURES

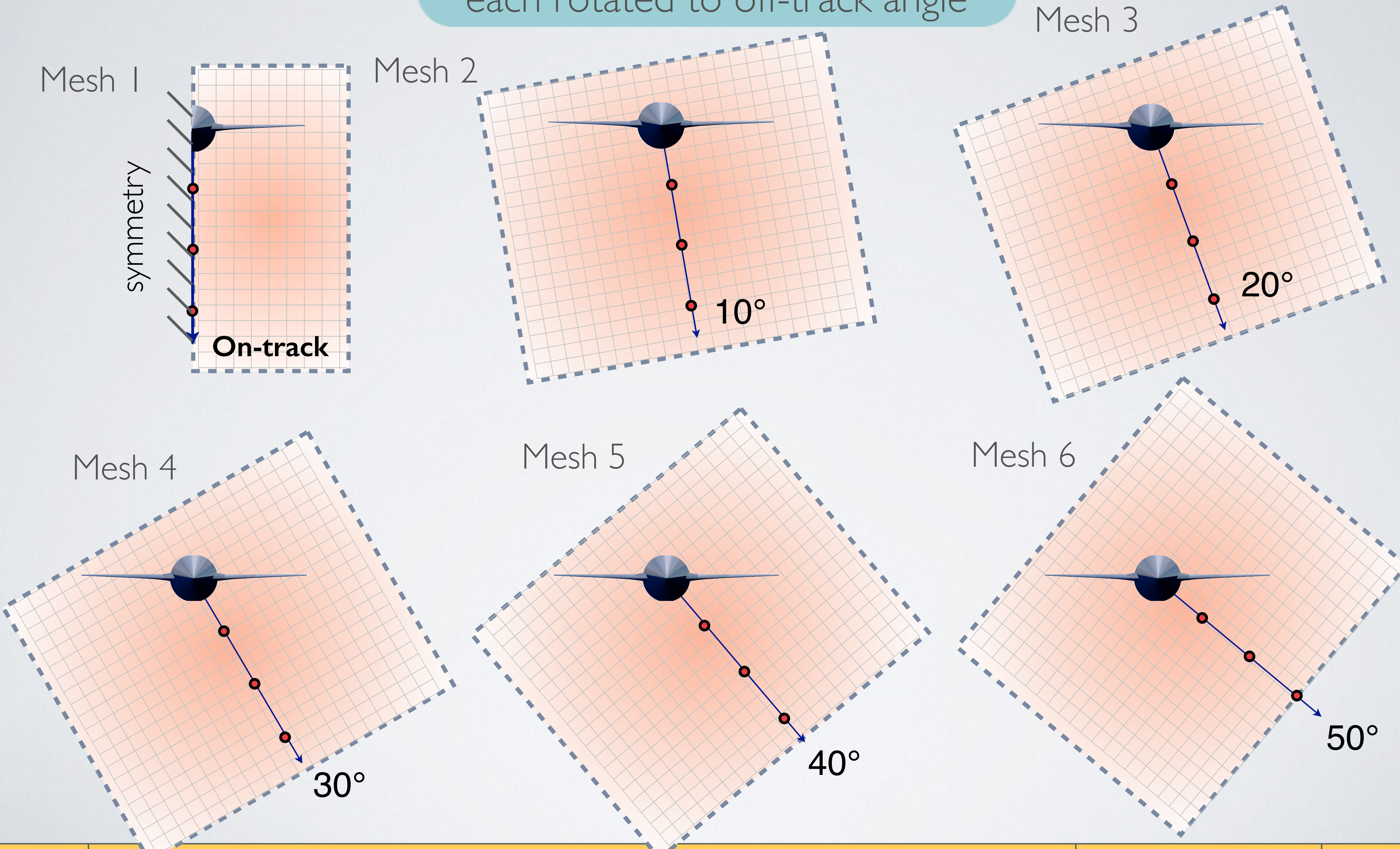


- Straightforward approach — ***compute all sensors with a single mesh***
- With Cartesian-aligned grids, off-track angles are misaligned, constraining aspect ratio and leading to **high cell-counts**.



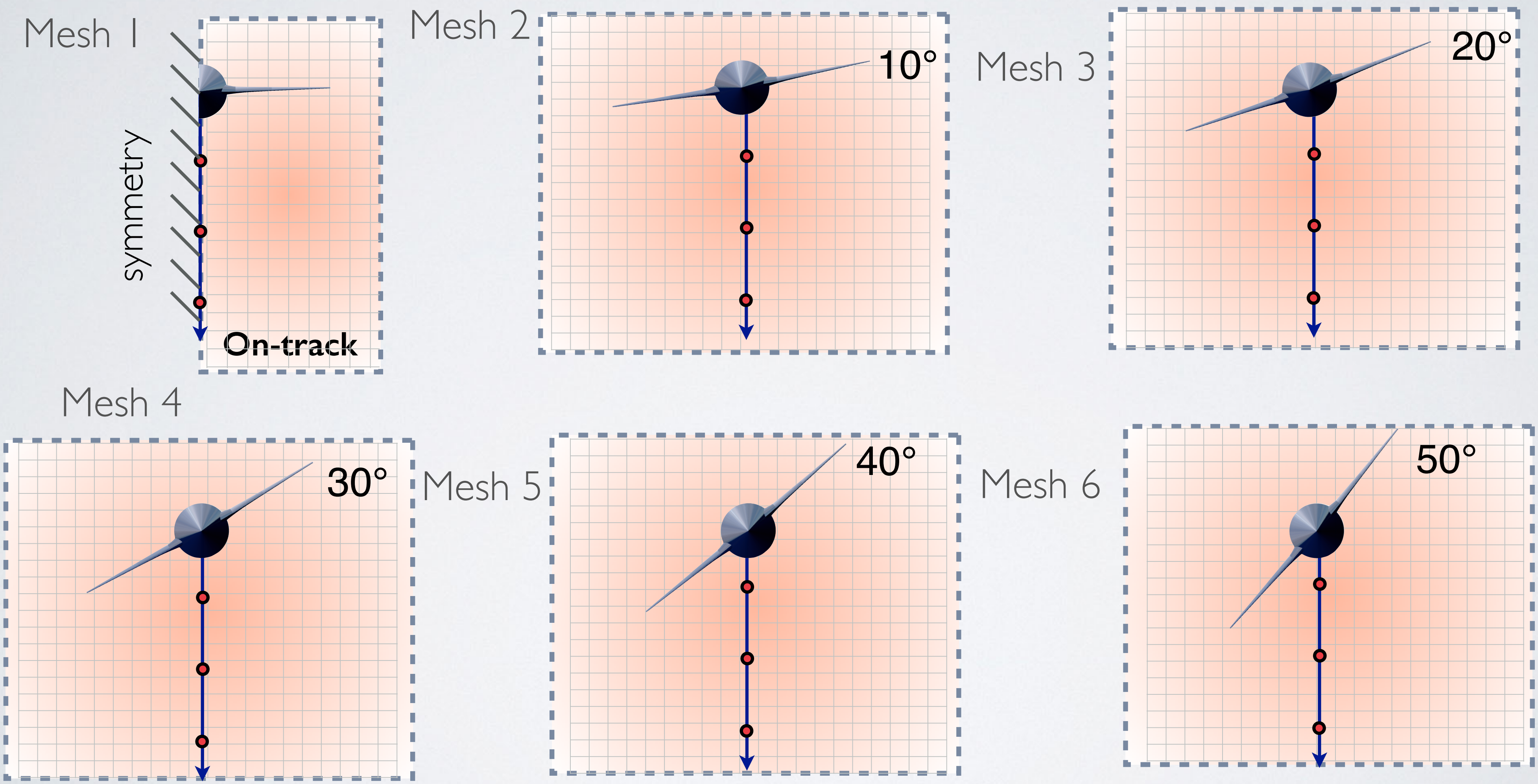
MESH SPLITTING

Use independent meshes,
each rotated to off-track angle

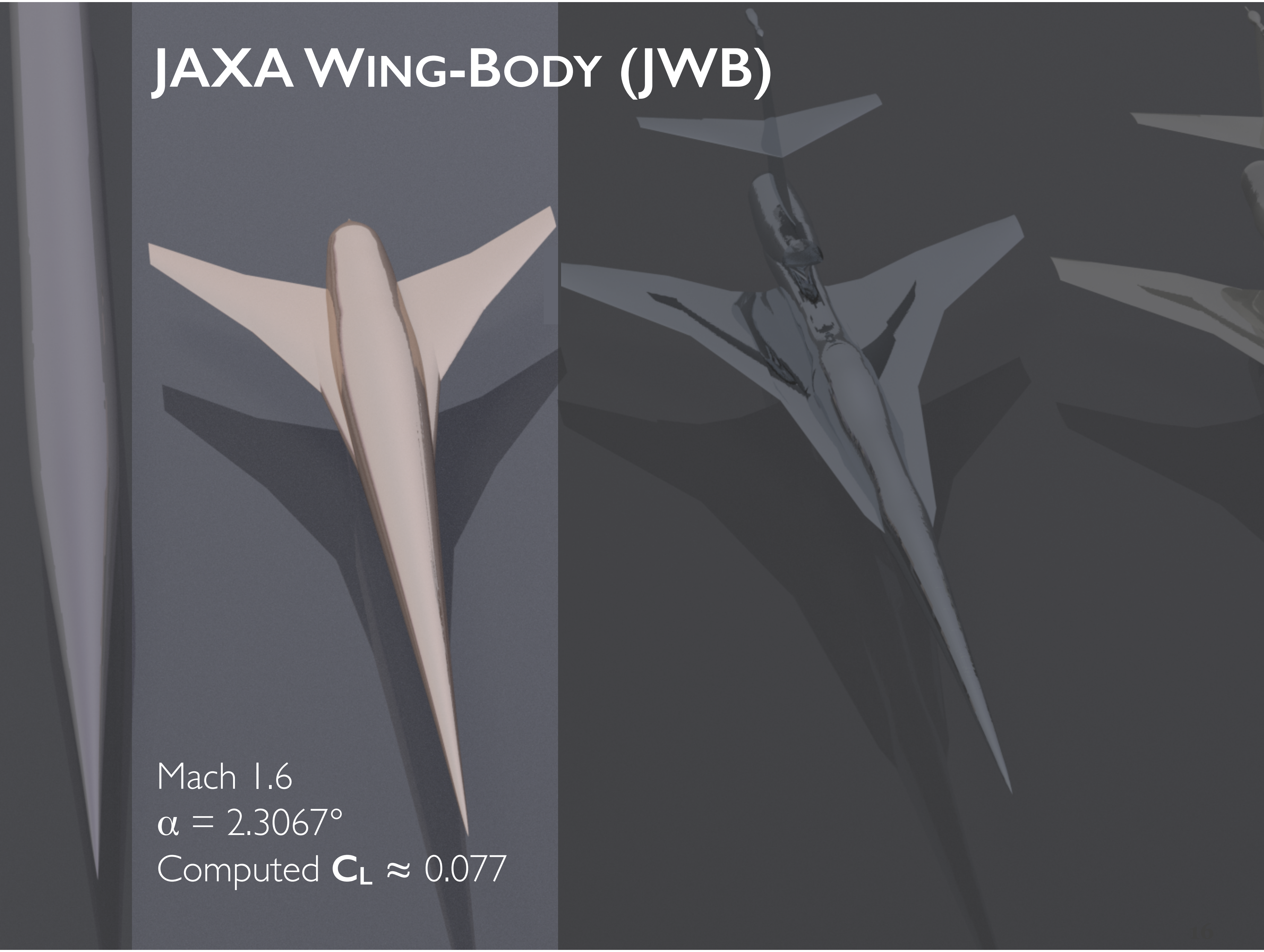


MESH SPLITTING

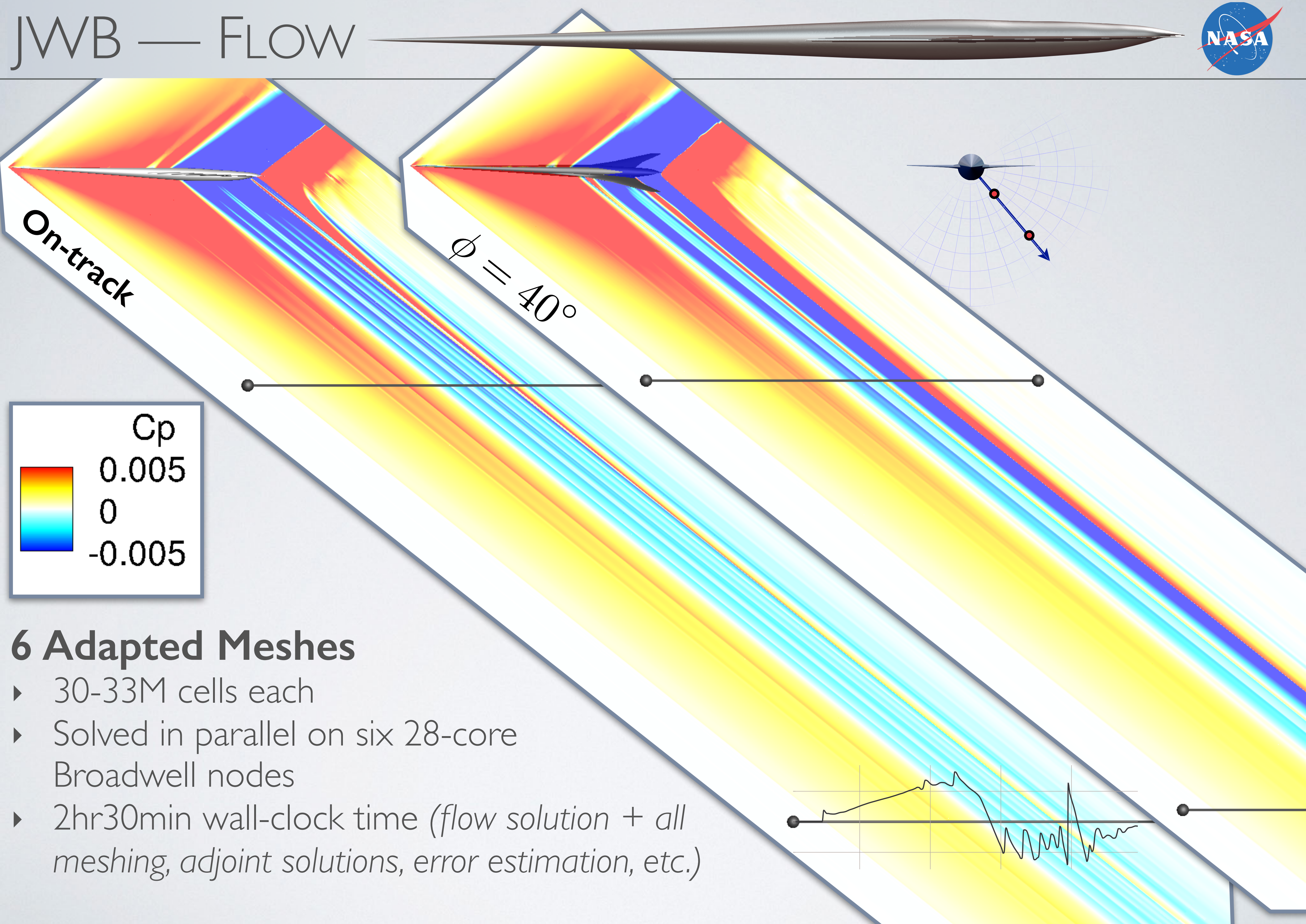
- Azimuthal alignment **improves quality/cost** and permits **higher stretching**
- Can run off-track angles **in parallel —** 6 compute nodes
- **Scriptable** *[new Cart3D scripts available]*



JAXA Wing-Body (JWB)



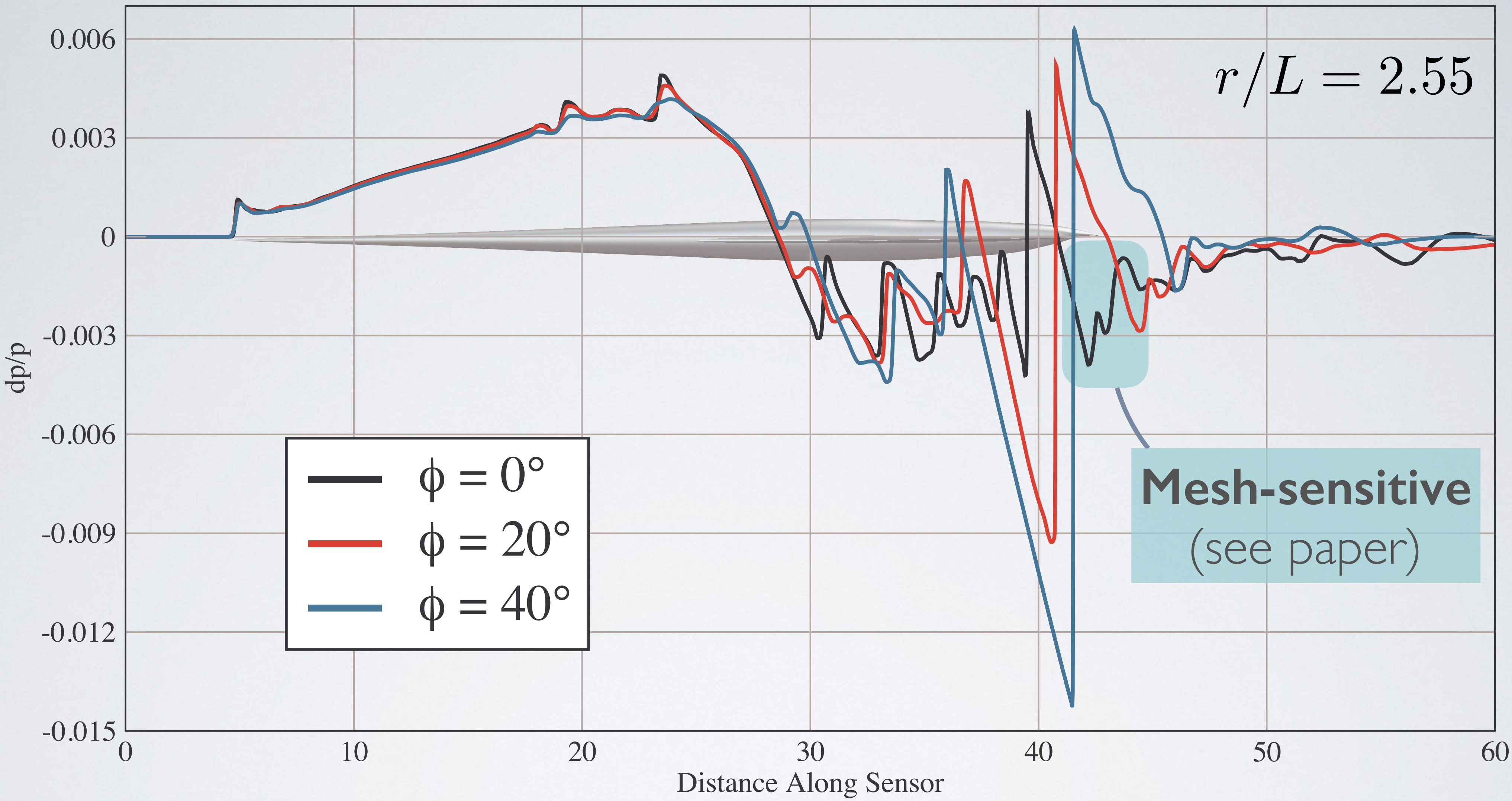
Mach 1.6
$\alpha = 2.3067°$
Computed $\mathbf{C_L} \approx 0.077$



6 Adapted Meshes

- 30-33M cells each
- Solved in parallel on six 28-core Broadwell nodes
- 2hr30min wall-clock time *(flow solution + all meshing, adjoint solutions, error estimation, etc.)*

JWB — Fine Mesh Signatures

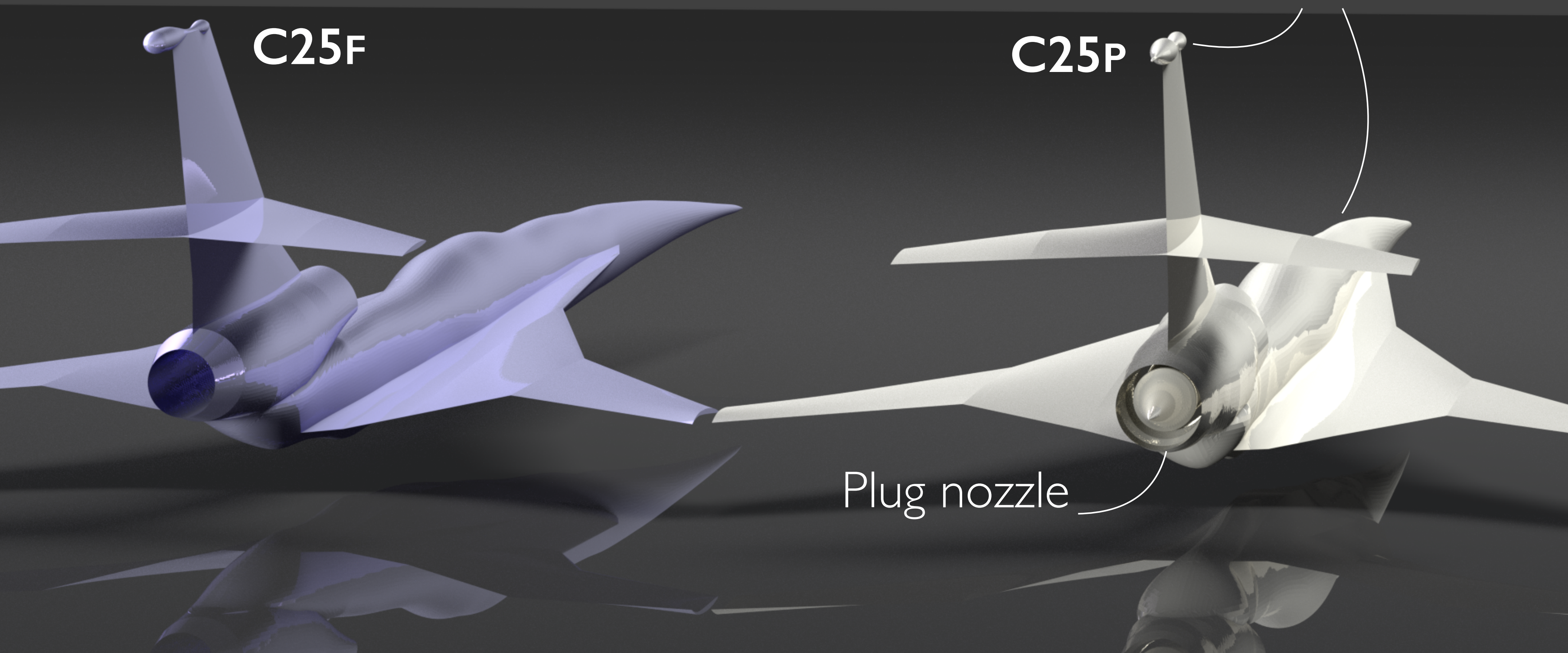


Each off-track angle — **30-33M cells** — **2hr 30min** on 28 cores

Includes flow solution + all meshing, adjoint solutions, error estimation, etc.

Concept 25D

(Government Reference Vehicle!)

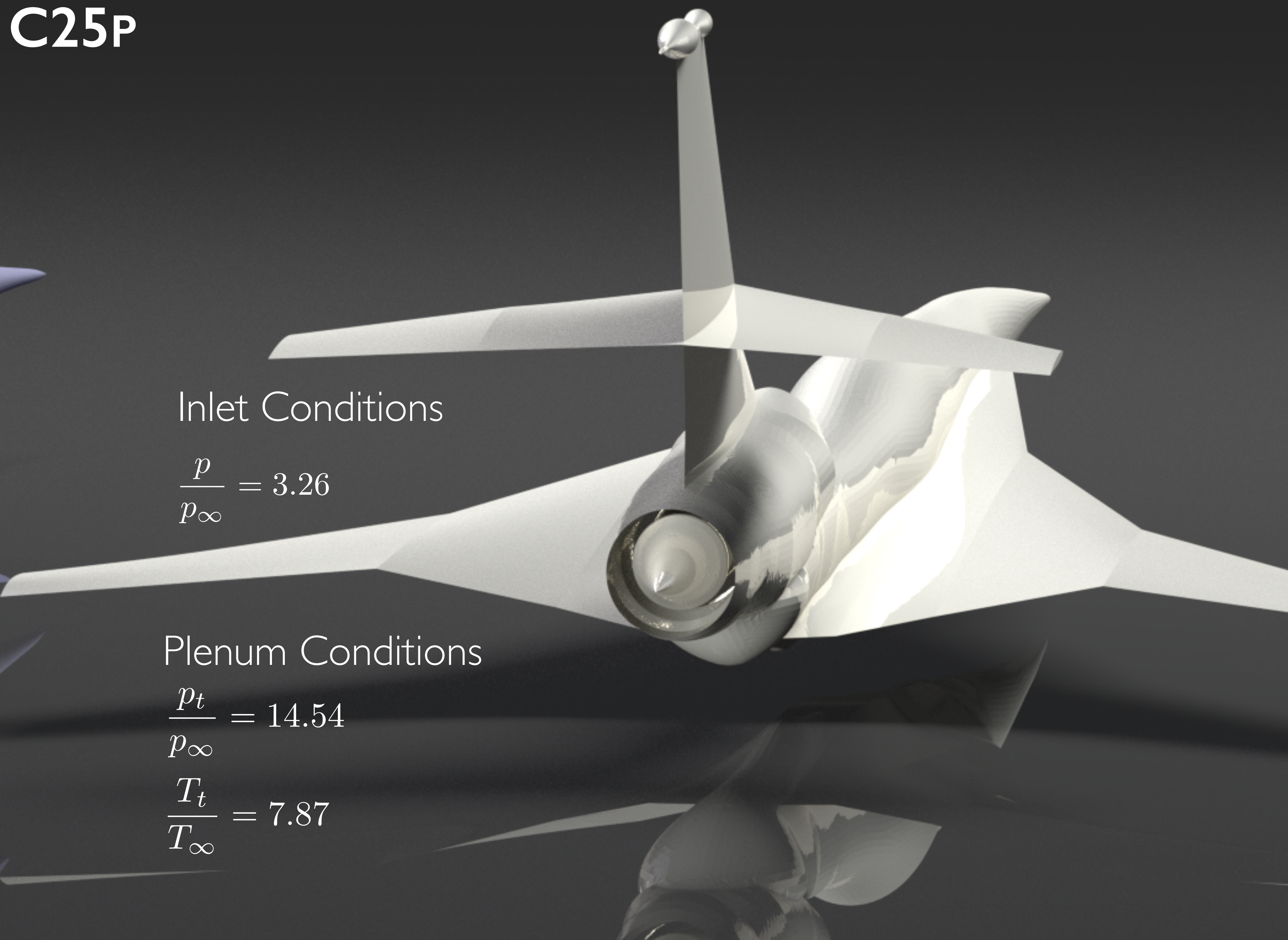


Mach 1.6

α = 3.375°

Computed $\mathbf{C_L}$ ≈ 0.068

C25P



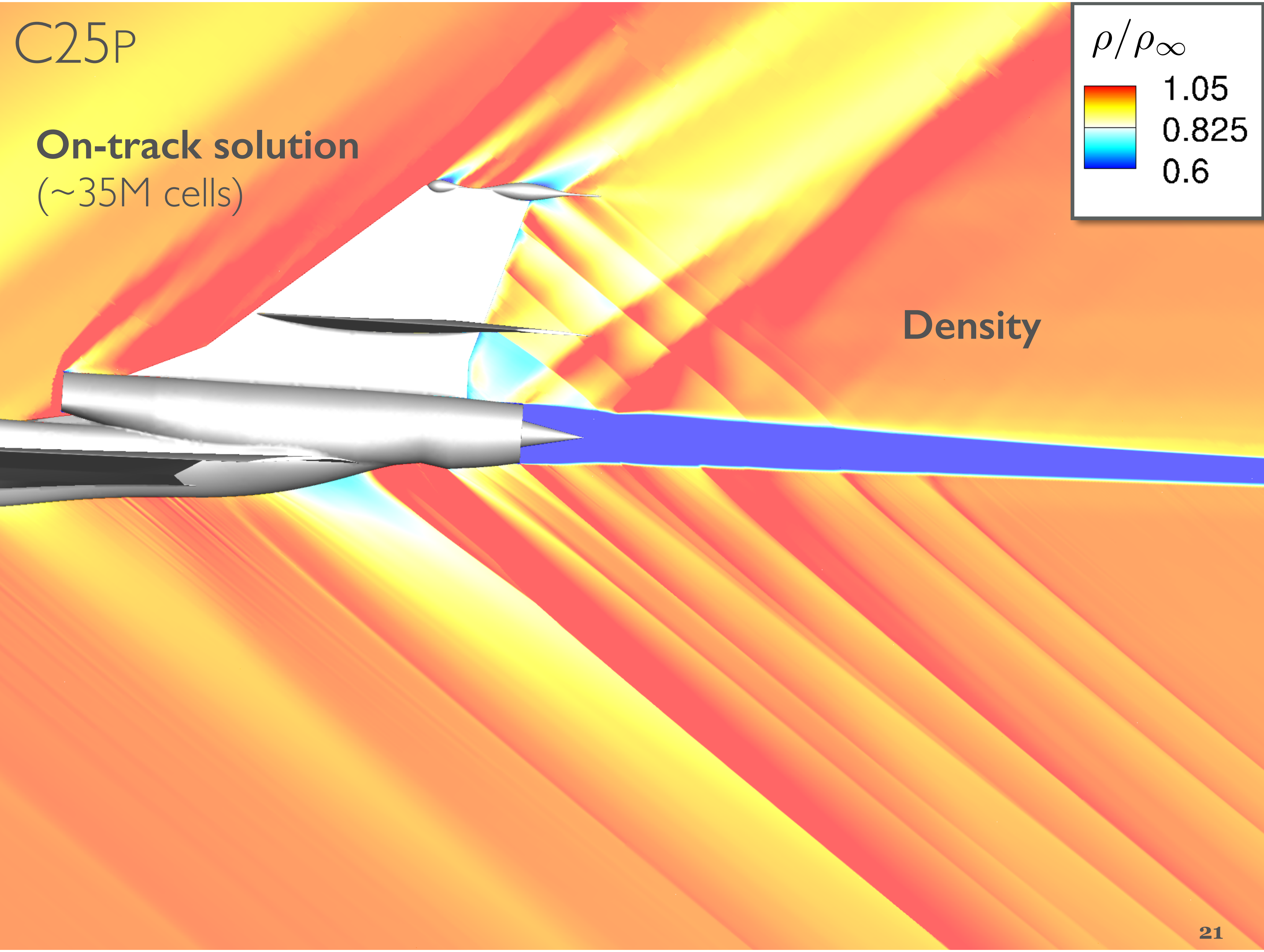
Inlet Conditions

$$\frac{p}{p_\infty} = 3.26$$

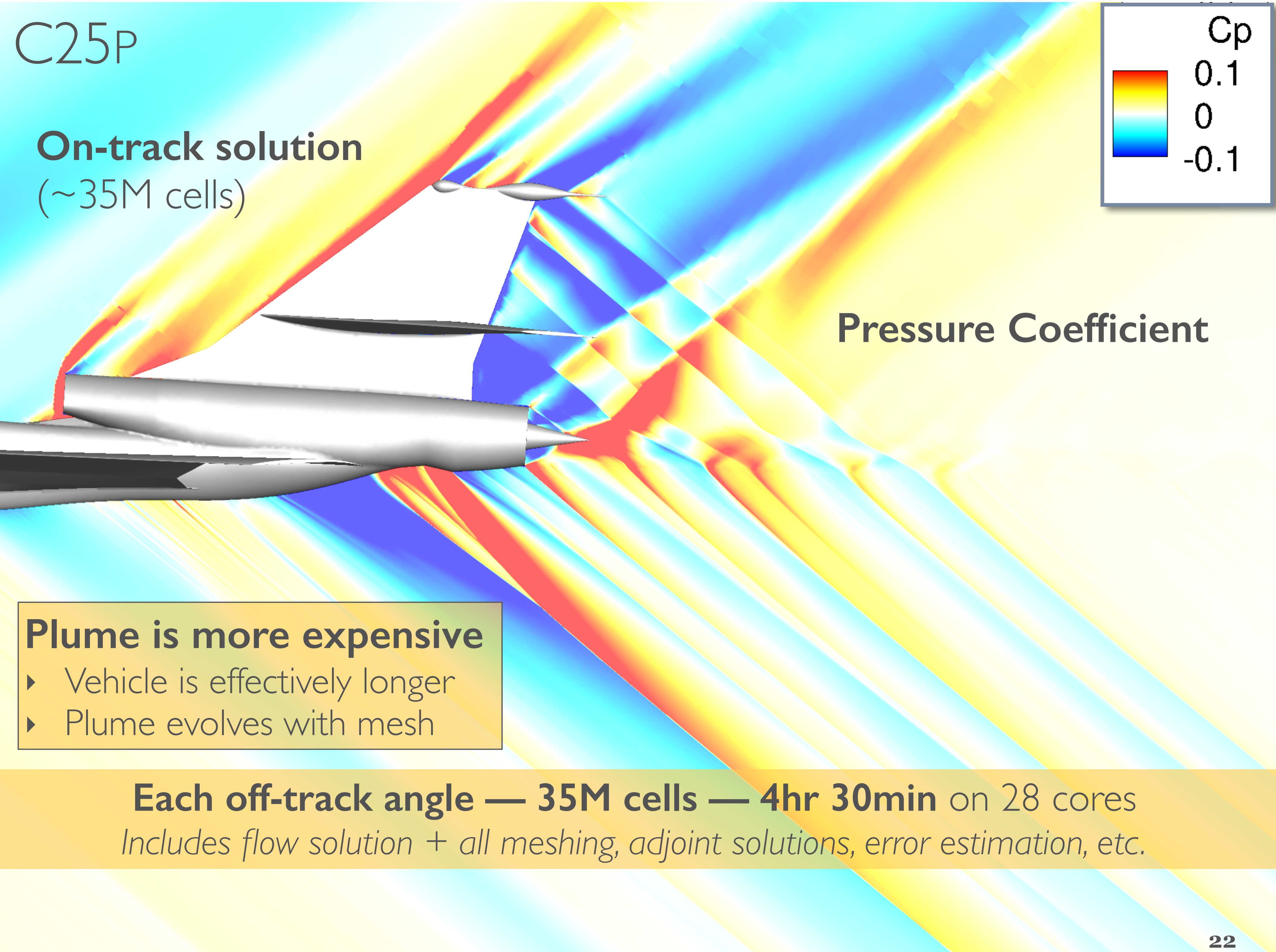
Plenum Conditions

$$\frac{p_t}{p_\infty} = 14.54$$

$$\frac{T_t}{T_\infty} = 7.87$$


C25P
On-track solution
(~35M cells)
Density
ρ/ρ_∞
1.05
0.825
0.6

C25P



On-track solution
(~35M cells)

Pressure Coefficient

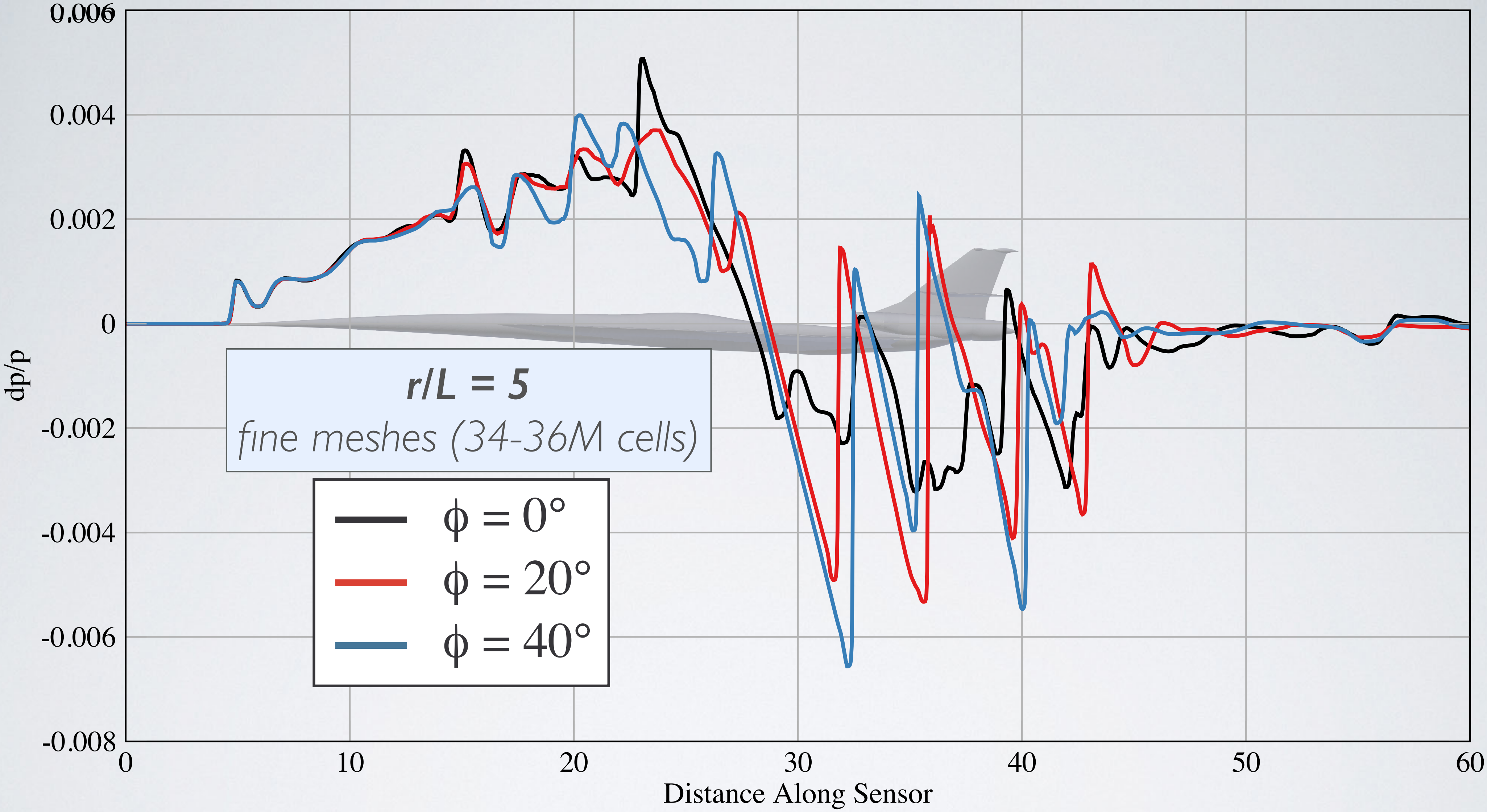
Plume is more expensive

- Vehicle is effectively longer
- Plume evolves with mesh

Each off-track angle — 35M cells — 4hr 30min on 28 cores

Includes flow solution + all meshing, adjoint solutions, error estimation, etc.

C25P — SIGNATURES



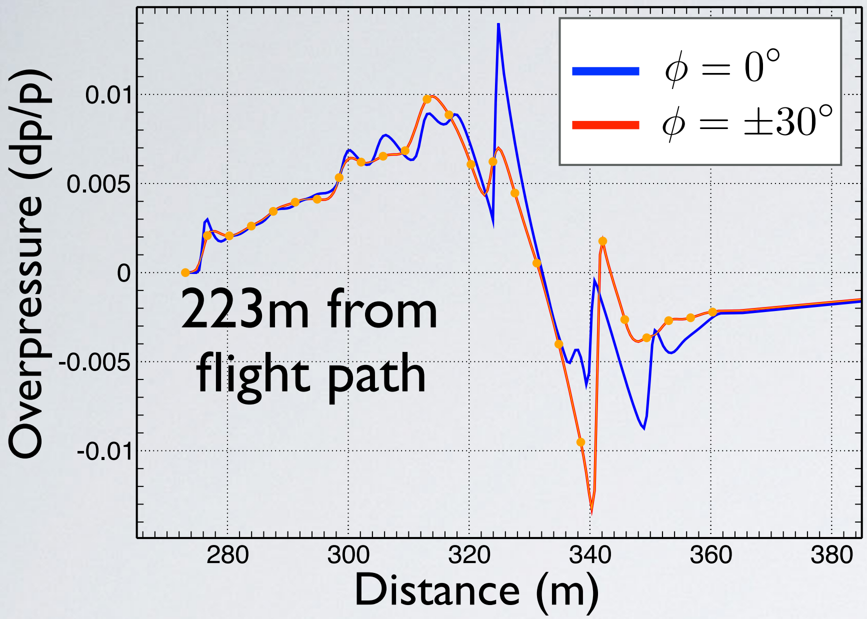
Local error estimates via extrapolation
*See AIAA Paper **2017-3255** for details*

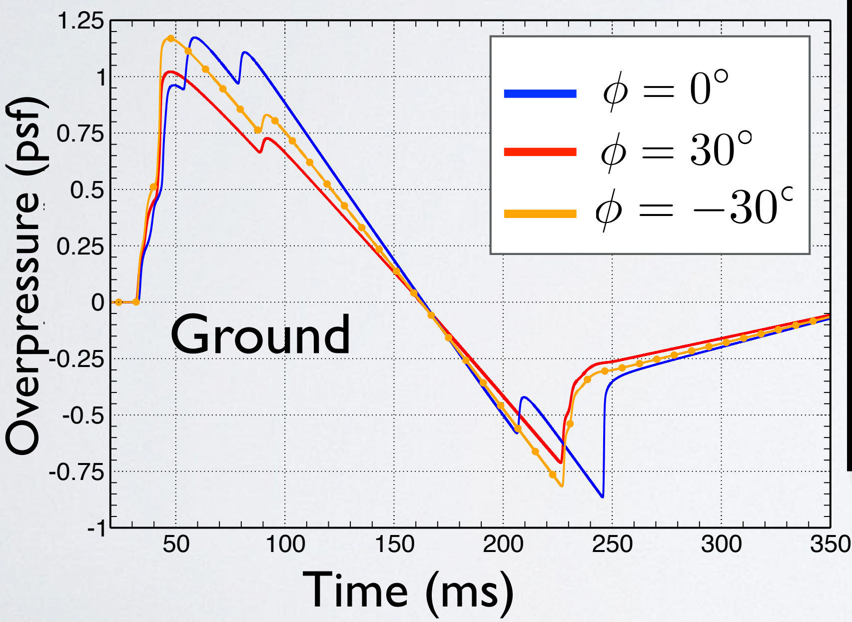
C25P (r/L=5, Φ = 0°)

Outline

- ✓ Nearfield Workshop
- Propagation Workshop — sBOOM
  - Numerical approach
  - Propagation Results:
    - Nearfield workshop signatures
    - Propagation workshop signatures
- Conclusions

Atmospheric Propagation with sBOOM



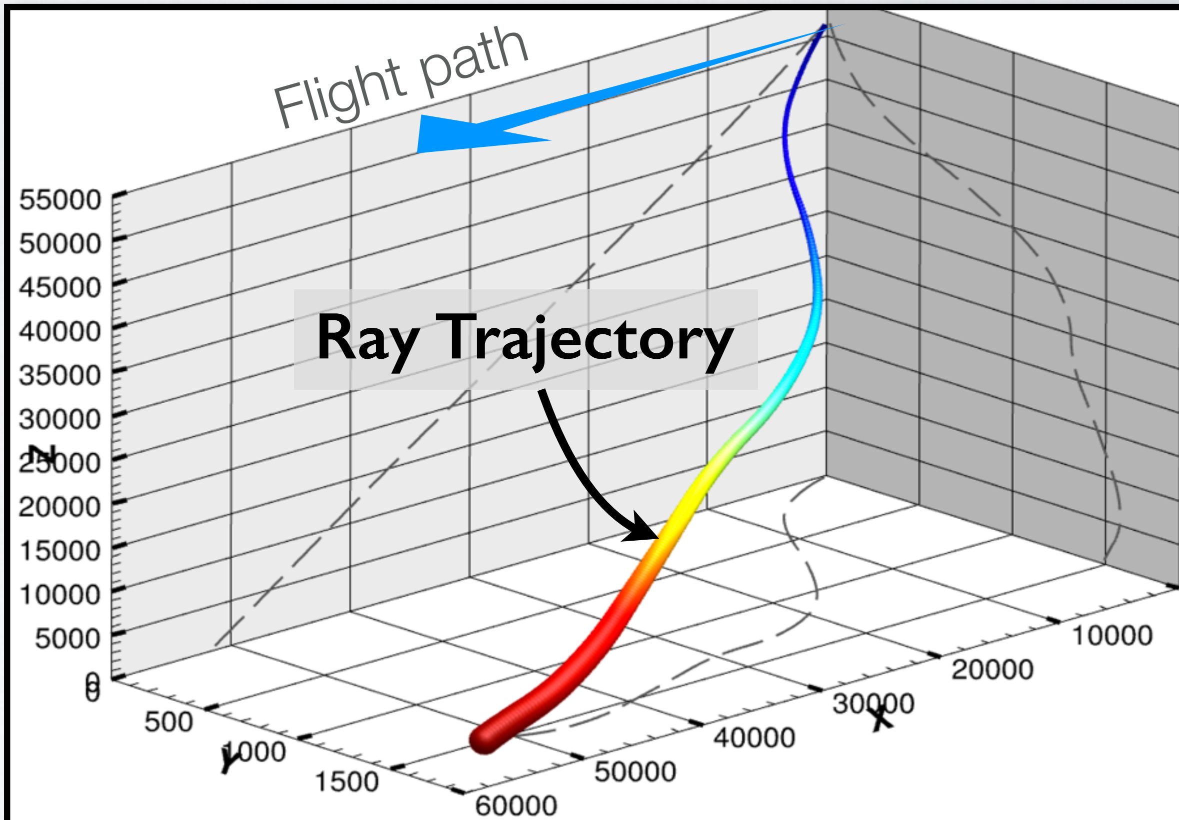


	+30°	0°	-30°
PLdB	89.2	92.7	91.1

LCASB

sBOOM

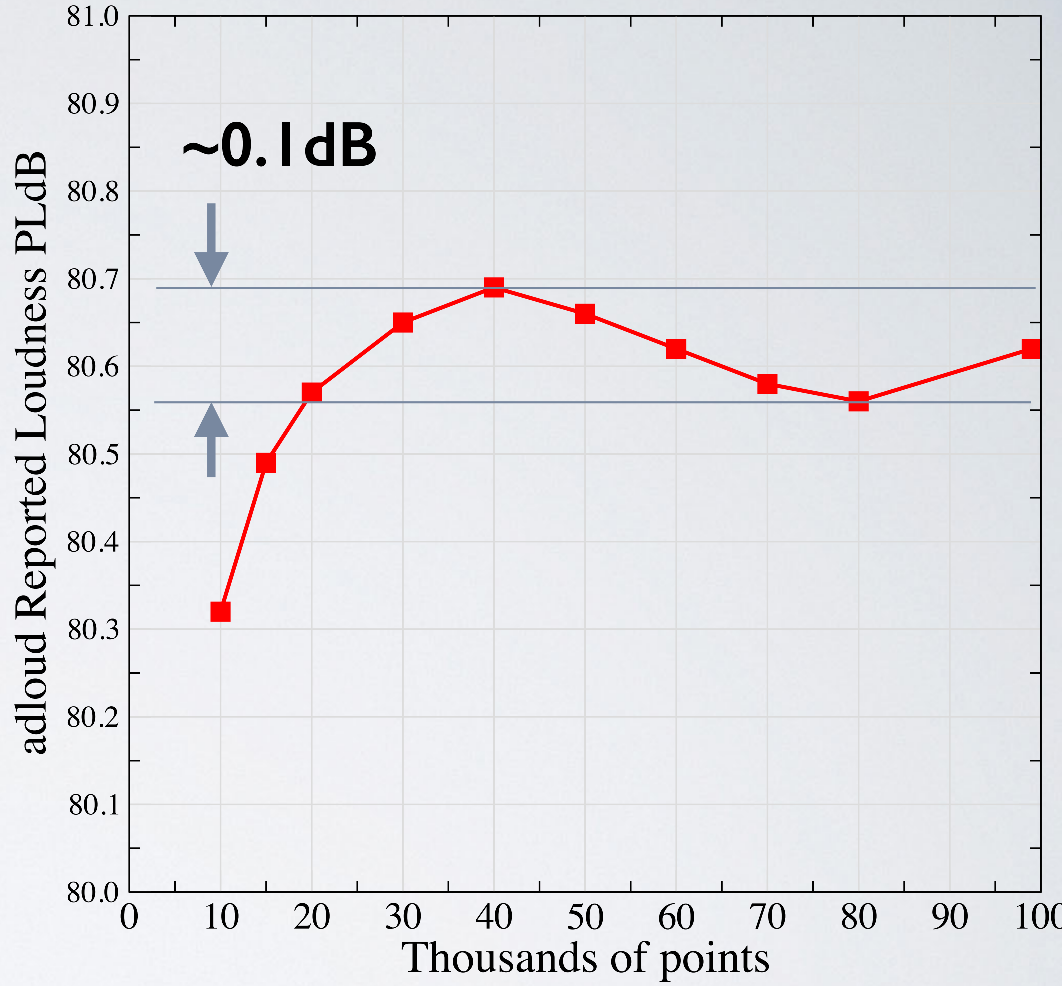
1. Ray-tracing
2. Quasi-1D, augmented Burgers' equation



(2011) Rallabhandi, ***"Advanced Sonic Boom Prediction Using the Augmented Burgers Equation"*** J. Aircraft

(1991) Shepherd & Sullivan, ***"A Loudness Calculation Procedure Applied to Shaped Sonic Booms"***

- **Discretization error**
  Finite difference solution of PDE on uniform grid
- **Input error**
  Input ~100X coarser than output
  Oversampling introduces high freq.
- **Mesh refinement studies**
  Numerical sources of error **~0.1dB**
  (cf. atmospheric variability of ~5 dB)
  But not clearly asymptotic



Perceived loudness (PLdB)

from r/L=5 on fine CFD mesh

Case	$\Phi = 0°$	$\Phi = 10°$	$\Phi = 20°$	$\Phi = 30°$	$\Phi = 40°$	$\Phi = 50°$
AXIE	78.1	—	—	—	—	—
JWB	79.5	76.5	78.2	**82.2**	81.6	76.6
C25F	78.1	80.4	80.1	**82.2**	80.1	73.3
C25P	80.4	81.3	78.3	**81.4**	78.7	73.3

CFD Mesh Convergence of Loudness

Perceived loudness (PLdB)
from r/L=5 on fine CFD mesh

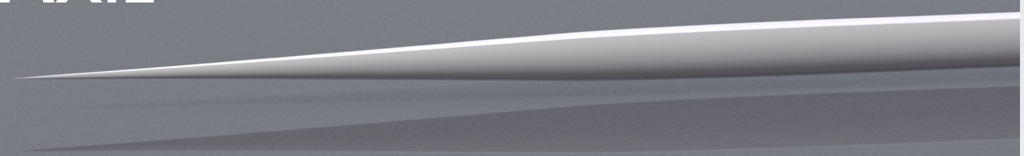
▲ ▼ **Δ PLdB** from coarse to fine CFD mesh

Case	$\Phi = 0°$	$\Phi = 10°$	$\Phi = 20°$	$\Phi = 30°$	$\Phi = 40°$	$\Phi = 50°$
AXIE	78.1 (▼*0.4*)	—	—	—	—	—
JWB	79.5 (▼*0.6*)	76.5 (▼*0.7*)	78.2 (▼*0.4*)	**82.2** (▼*1.5*)	81.6 (▼*0.1*)	76.6 (▲*0.5*)
C25F	78.1 (▲*0.8*)	80.4 (▲*0.6*)	80.1 (▼*0.1*)	**82.2** (▲*0.8*)	80.1 (▲*0.6*)	73.3 (*0.0*)
C25P	80.4 (▼*0.5*)	81.3 (▼*0.5*)	78.3 (▼*0.3*)	**81.4** (▼*0.6*)	78.7 (▼*0.4*)	73.3 (▼*1.6*)

- Typically **<1 dB change** from coarse to fine CFD mesh (max 1.6 dB)
- But — do **not** demonstrate asymptotic convergence.

Propagation Workshop Cases

AXIE



Lref = 43m (141 ft)

Conditions:

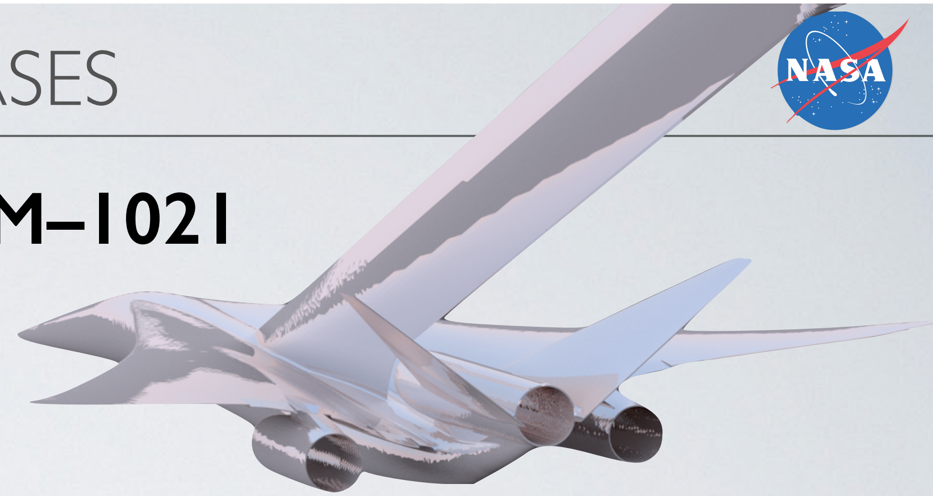
$M_\infty = 1.6$

Altitude = 15.8 km (~52K ft)

Profiles:

- ISO Standard Atmosphere
- ISO Std. Atm. with 70% humidity
- Hot day, coastal Virginia
- Hot dry day, Edwards AFB

LM–1021



Wind tunnel model from SBPW1 (2014)

Lref = 71m (233 ft)

Conditions:

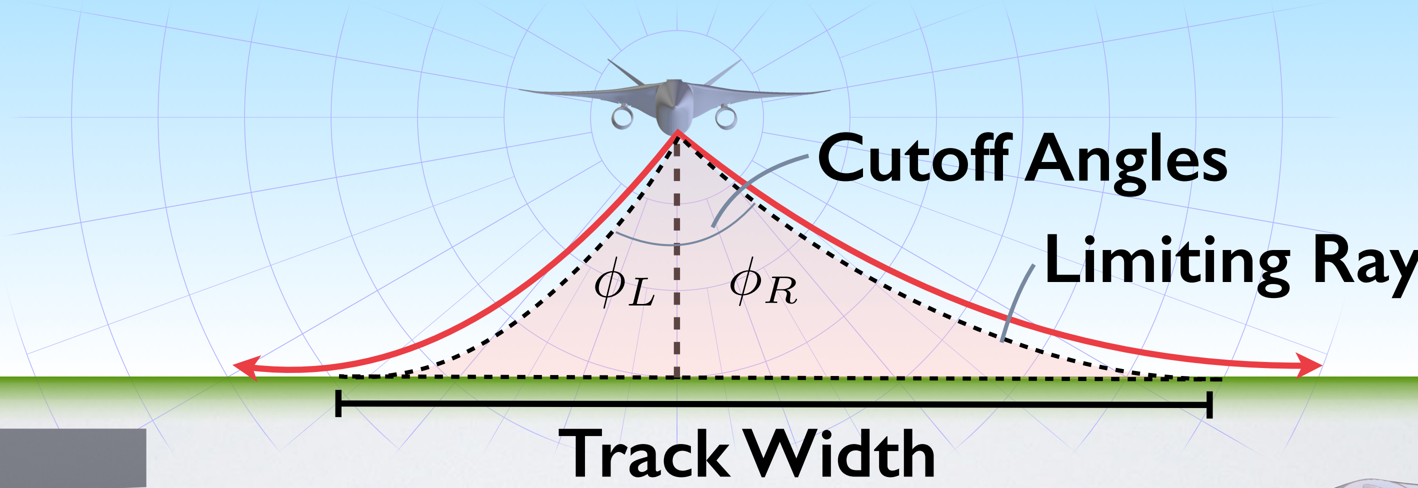
$M_\infty = 1.6$

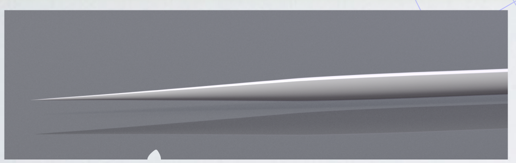
Altitude = 16.7 km (~55K ft)

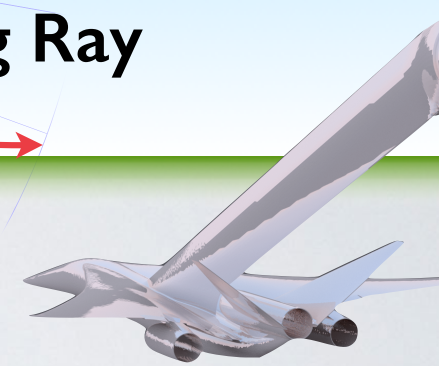
Profiles:

- ISO Standard Atmosphere
- ISO Std. Atm. with 70% humidity
- 2 consecutive winter days in Green Bay, WI

Boom Footprint





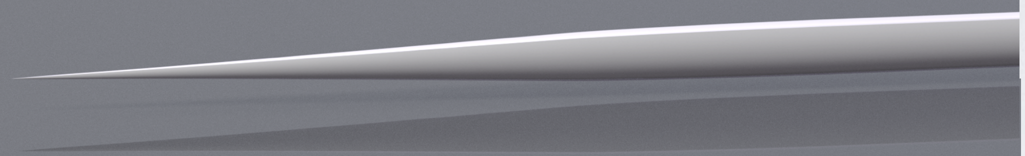


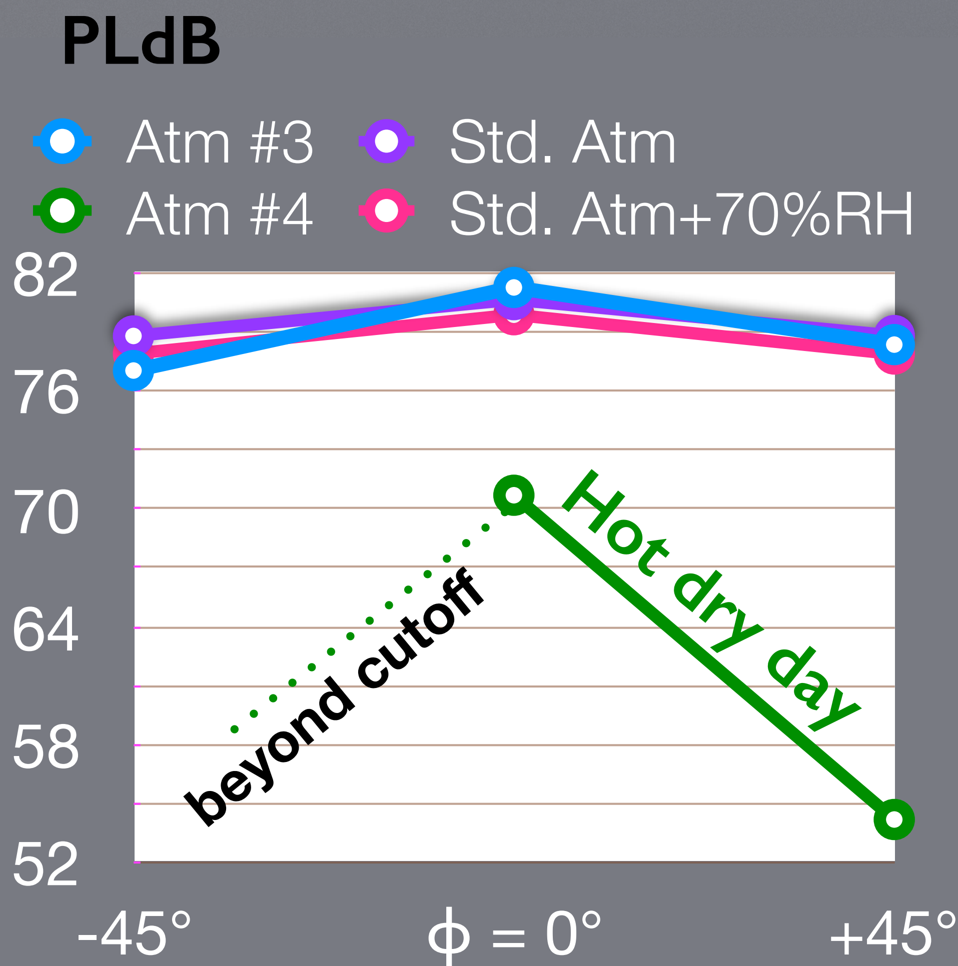
Axie	Cutoff		Track Width
Std. Atm	±50°		69 km
Atm # 3	-53°	50°	85 km
Atm # 4	-44°	47°	72 km

LM–1021	Cutoff		Track Width
Std. Atm	±50°		71 km
Atm # 1	**-74°**	57°	87 km
Atm # 2	-59°	65°	**111 km**

LOUDNESS

AXIE





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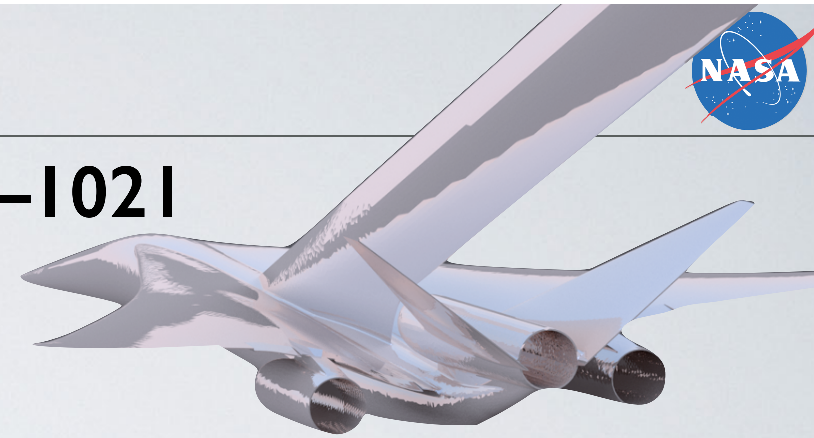
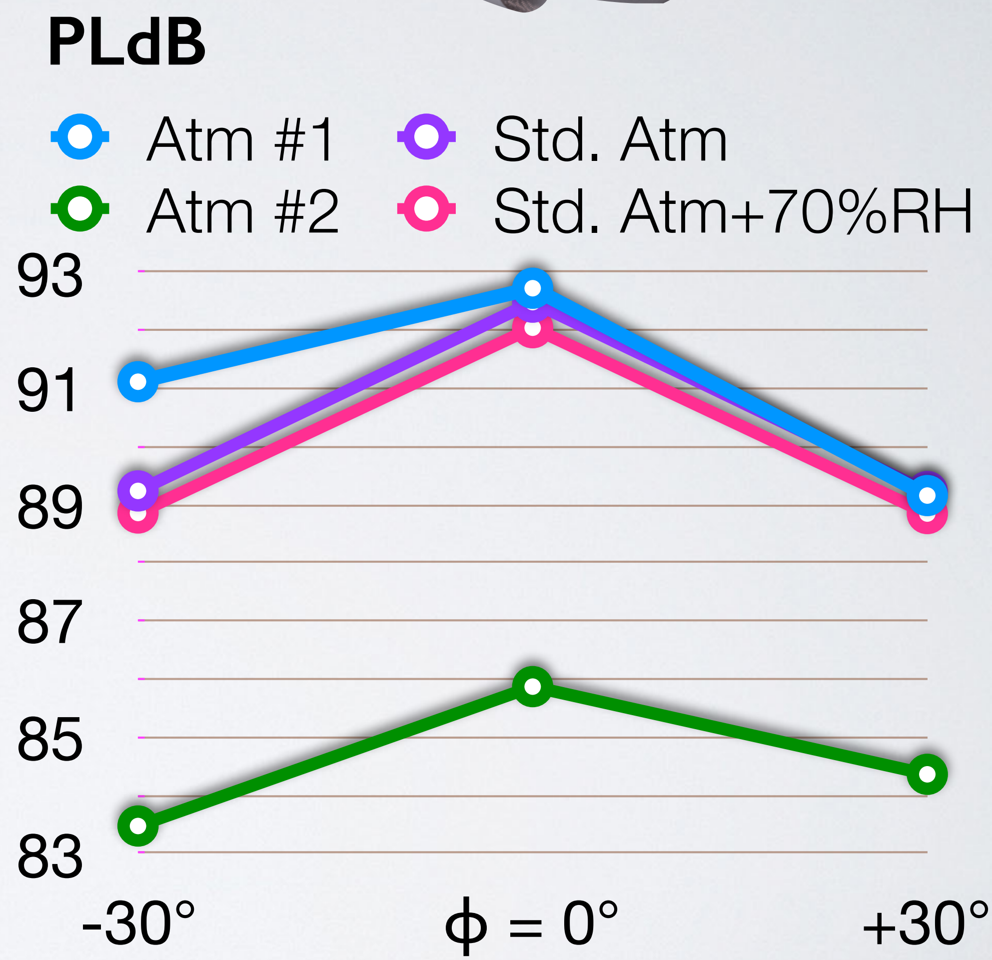
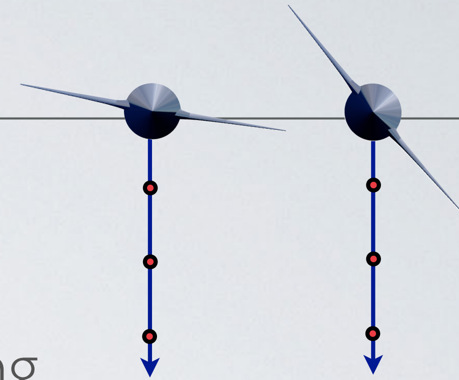
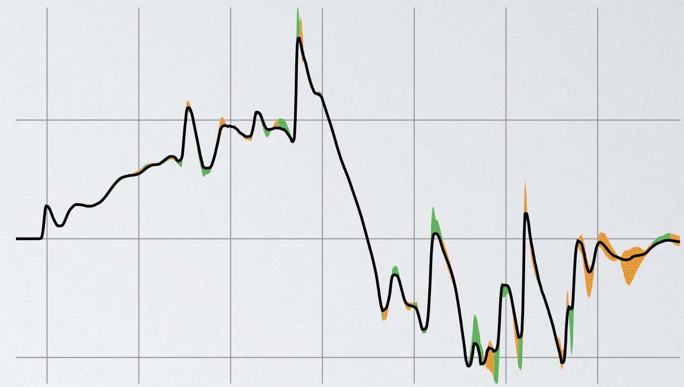






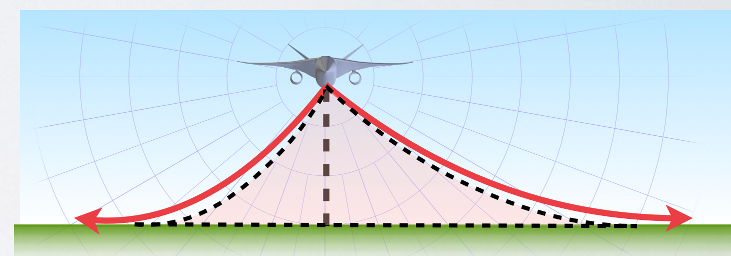
Nearfield with Cart3D

- Improved efficiency — off-track angles on parallel meshes, azimuthal alignment, stretching *[new scripts for Cart3D users]*
- Method for assessing local signature mesh convergence *[scripts available]*



Propagation with sBOOM

- Major atmospheric variability: 2-5 dB typical, 10-20 dB in extreme cases.
- With cross-wind, up to **75° off-track** can hit ground and **track widths widen by 50%**
- Asymptotic convergence of nearfield signature does not imply same of noise



QUESTIONS?

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